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14. ABSTRACT

This thesis documents the development and application of a branch and bound enumeration algorithm for the selection of an optimal flood control plan. An application is presented in which optimal reservoir flood control plans for a three reservoir system are selected.

Computer program HEC-5 is used to simulate the reservoir system to determine the modified condition flow-frequency curves, EAD is used to evaluate expected annual damage reductions and the HEC-DSS Program was used to manage the large amounts of data required for the computations. The branch and bound enumeration algorithm provides a systematic evaluation of plans with the HEC programs and expedites identification of the optimal plan by elimination the need to evaluate all alternative plans.

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Preface

This thesis was submitted by Teresa Bowen in partial satisfaction of the requirements for the degree of Master of Science in Engineering in the Graduate Division of the University of California, Davis, CA. Much of the developmental work was conducted while Ms. Bowen was a temporary employee at HEC. The application of HEC simulation programs and the Flood Damage Analysis Package were utilized for this research. Dr. David Ford, a member of the thesis committee, was an HEC employee during the conduct of this research. He has been a proponent of the Branch-and-Bound Enumeration procedure for the systematic evaluation of planning alternatives. This thesis is published as an HEC Research Document in support of their efforts to make the procedure more available to planning professionals.

Chapter 1

Introduction

Flood damage analysis is performed to provide quantitative information of the social cost of flooding and to provide a basis for formulating, evaluating, and selecting the optimal flood-damage-mitigation plan. The Water Resources Council Principles and Guidelines (1983), which guides water resources planning studies for the Corps and all Federal agencies, requires that the plan selected for implementation be the one that yields the maximum net benefit consistent with environmental, institutional, social and financial requirements. A flood-damage-mitigation plan consists of a set of measures which are intended to function as a system to mitigate, or reduce, flood damages at one or more sites in a basin. A measure is a single proposed action at a site and includes a wide-range of alternatives from a reservoir, to a levee, to floodproofing of structures to the implementation of a new set of operating rules for an existing reservoir system.

Complete plans are formed by combining various potential measures at all the sites in the basin. Evaluation of the net benefit of a proposed plan requires hydrologic, hydraulic, and economic analyses of the system. Plan selection can then be done by evaluating all possible plans (combinations of measures) and selecting the plan with the maximum net economic benefit (the optimal plan). For a few sites with 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. Generalized simulation models are often the tools selected to perform the analysis and evaluation of the proposed alternative plans. However, in large systems with many sites and components, evaluation of every possible alternative system cannot be practically accomplished. For example, to determine the optimal plan of a six-site system with five alternative measures proposed at each site, 7776 (6^5) combinations of alternative measures would have to be analyzed and evaluated. A method to efficiently and with certainty identify the optimal plan is needed for such a system.

Various systems analysis techniques are used in water resources planning. The goal of systems analysis is to find an optimum decision for system operation, meeting all constraints while maximizing or minimizing some objective function. The most common techniques are linear programming and dynamic programming. These methods pose several disadvantages in the analysis of water resource systems. The most important disadvantage is that optimization models implicitly examine all possible decision alternatives, while water resources planning is limited to selecting between a finite number of discrete alternatives.

A systems analysis technique called branch-and-bound enumeration has been applied in the water resources planning field to solve problems of selecting, sizing, sequencing, and scheduling projects. Branch-and-bound methods are general schemes of finding an optimum of a very large number of discrete points, or alternative plans. Branch-and-bound is therefore particularly applicable to the problem of flood control plan selection.

This work uses a branch-and-bound algorithm to expedite the plan selection process between discrete alternative plans. The plans are evaluated using Hydrologic Engineering Center simulation models to perform the hydrologic, hydraulic, and economic analysis. HEC programs are widely used and are based on accepted engineering and economic principles.

The first part of this research focuses on development of a branch-and-bound enumeration algorithm. The second major portion of this work is to link the routine to existing HEC simulation programs. This thesis presents the findings of the research.

Chapter 2

Engineering and Economic Considerations in Formulating Flood-Damage-Mitigation Plans

The major objective of system formulation is to determine what combination of measures will produce the "best" (optimal) solution. The following information is useful in achieving this objective:

1. An understanding of the effects of each measure and under what conditions it is effective.
2. A systematic strategy for formulation to achieve the stated objective.
3. A means to assess the overall performance of each system.
4. An efficient, systematic approach to identify the "best" plan.

The following sections discuss the methodology for computing flood damages, the effects of various floodplain management measures on hydrologic and economic relationships, and evaluation tools used to assess the system performance.

The remainder of the report explores the fourth step and final objective of system formulation, that of identification of the optimal plan.

2.1. Flood Damage Computation Methodology

The principal reason for computing flood damage is to determine the effectiveness of different flood plain management plans. The benefits of a project are measured in terms of a reduction in flood damages, also called an inundation reduction benefit. In order to evaluate flood damages over the life of a project, the concept of expected annual flood damage is used. Expected annual damage is the frequency-weighted sum of damage for the full range of possible damaging flood events and can be viewed as what might be expected to occur in the present or any future year. It represents the annual damage for a particular set of hydrologic, hydraulic and damage conditions.

Expected annual flood damage computations may be performed by two distinctly different approaches. The first way is to compute the average annual damage value from historic records of all floods observed. Historic records are often short and the magnitude and frequency may not adequately represent the magnitudes and frequency of future floods. A plan selected based on historic events may not be the optimal plan in the long run.

Another approach is the frequency method, where measures are evaluated by determining their effects on the basic relationships that determine the damage, and computing the expected annual damage. Data is gathered from specific flood events, observed or synthetic, and the damage value is weighted according to its percent chance of exceedence. This exceedence-damage relationship can be integrated numerically to yield the expected annual damage (also called average annual damage).

The exceedence frequency-damage relationship can be developed using several different combinations of stage[1], flow, damage, and frequency data. The easiest way is to relate stage or flow to damage and to relate the same parameter to exceedence frequency. If the damage and frequency data are not directly related to a common parameter then another relationship must be used. This is commonly the rating curve or stage-flow function. Thus, if damage is expressed as a function of stage and exceedence frequency as a function of flow, damage can be related to frequency with the stage-flow function. Figure 1, excerpted from the EAD Users Manual (HEC, 1984), summarizes the basic technical analysis, derived functional relationships, and general processing to develop the damage-frequency function.

Because stage, flow, frequency and damage relationships vary along a river, it is common practice to divide a river into reaches and specify a set of relationships to represent conditions for that reach. An index location is selected within the reach and a single stage- or flow-frequency relationship and stage-flow relationship are applied at that location and are considered representative of these variables for the entire reach. If damage is categorized for analysis, several stage- or flow-damage relationships may be used in the reach.

2.2 Effects of Floodplain Management Measures on Stage, Damage, Flow, and Frequency Functions

Flood-damage-mitigation measures protect damageable property in two ways:(1) by modifying the flow of flood waters, and (2) by reducing the potential for flood damage. A third category of flood-damage-mitigation measures do not reduce the damages at all but reduce the effects by redistributing the loss burden through flood insurance and other programs. Measures in the first category are also known as flood control projects and often involve a costly structural solution. Typical measures are reservoirs, floodwalls, levees, channel modifications, and diversion projects. Measures designed to manage water can alter various hydrologic and hydraulic relationships at specific locations in a basin. The measures in the second category are also called nonstructural measures because no large-scale construction usually is required for implementation. These measures are usually less costly than structural measures and therefore often are implemented locally. Floodproofing, relocation, flood warning and land-use control are typical measures in this category. Measures designed to avoid flood damages rather than confine flood waters alter only economic relationships and are evaluated by altering the damage functions. The complexities, varying nature, and scope of flood-damage-mitigation measures requires an experienced planner in the formulation process. Evaluation, however, is more straightforward. Any type of measure may be evaluated as long as the corresponding damage functions can be defined.

Enlightened flood control planning today explores alternative measures in all categories during the preliminary plan formulation stage. Detailed plans are developed which are comprised of a combination of structural and nonstructural measures and perhaps flood insurance programs, too. The analysis and evaluation of structural and nonstructural measures is discussed in the following sections.

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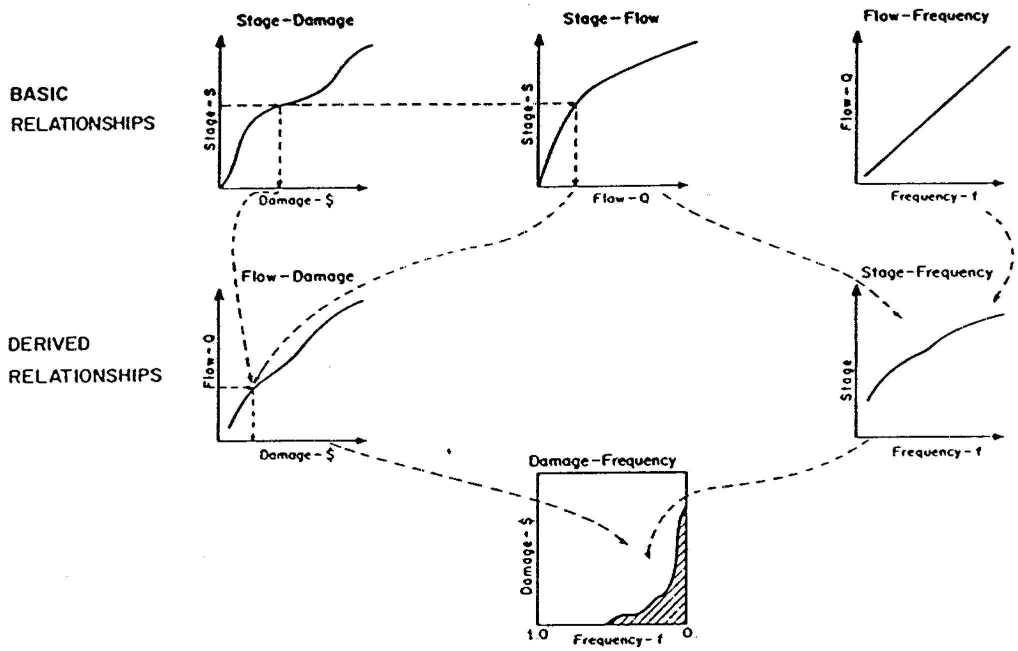
[1] The term stage is used in this report to represent both stage (distance above a certain local datum) and elevation (distance above a common datum for the entire study area.)



The basic and derived evaluation relationships are shown above. Concepts important to their construction are described herein.

Stage-Flow Relationship: This is a basic hydraulic function that shows for a specific location, the relationship between flow rate and stage. It is frequently referred to as a 'rating curve' and is normally derived from water surface profile computations.

Stage-Damage Relationship: This is the economic counterpart to the stage-flow function and represents the damage which will occur for various river stages. Usually the damage represents an aggregate of the damage which could occur same distance upstream and downstream from the specified location. It is usually developed from field damage surveys.

Flow-Frequency Relationship: This defines the relationship between exceedance frequency and flow at a location. It is the basic function describing the probability nature of streamflow and is commonly determined from either statistical analysis of gaged flow data or through watershed model calculations.

Damage-Frequency Relationship: This relationship is derived by combining the basic relationships using the common parameters stage and flow. For example, the damage for a specific exceedance frequency is determined by ascertaining the corresponding flow rate from the flow-frequency function, the corresponding stage from the stage-flow function and finally the corresponding damage from the stage-damage relationship. Any changes which occur in the basic relationships because of watershed development or flood plain management measure implementation will change the damage-frequency function and therefore the expected annual damage that is computed as the integral of the function (area underneath).

Other Functional Relationship: The flow-damage relationship is developed by combining the stage-damage with the stage-flow relationship using stage as the common parameter. The stage-frequency relationship is developed by combining the stage-flow with the flow-frequency relationship using flow as the common parameter. The damage-frequency relationship could then be developed as a further combination of these derived relatiohsips.

Figure 1
Basic and Derived Realtionships

2.3 Criteria for Plan Selection

The Water Resources Council's Principles and Guidelines of 1983 define the primary goal of implementing flood-damage-mitigation plans as enhancement of the National Economic Development (NED) account. From the NED standpoint, the best plan is the plan that yields the maximum net benefits (benefits minus cost). The cost is the sum of capital cost, operation, maintenance, power, replacement, and any other costs related to plan implementation. The benefit is the difference between flood damage with base conditions and flood damage under the same hydrologic conditions with the implemented plan (modified condition). The single objective of plan selection is to select the plan with the maximum net benefit, consistent with environmental, institutional, social and financial requirements. However, no computer model can replace the judgement of an experienced planner or engineer. A simulation model can greatly aid the engineer in the analysis and evaluation and an optimization model can help in selection of the "best" plan, but it is the only the engineer who can ultimately make the decisions.

Chapter 3

System Formulation Strategies

3.1 Systems Analysis Models

A system is best in terms of the national economic criteria if it yields system net benefits that exceed those of any other feasible system. When there are only 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. The analysis of a complex water resources system may involve thousands of decision variables and constraints and exhaustive evaluation of all feasible alternative systems cannot be practically accomplished. For this instance, a strategy is needed that reduces the number of alternatives to be evaluated to a manageable number while providing a good chance of identifying the best system. Once the objectives and constraints have been determined, most problems lend themselves to solution techniques developed in the fields of operations research and management science. Many successful applications of optimization techniques have been made in reservoir operation planning studies. Extensive literature review of the subject of optimization of reservoir operations shows that no general algorithm exists (Yeh, 1985). The choice of methods depends on the characteristics of the reservoir system being considered, the availability of data, and on the particular system objectives and constraints. In general, the available methods can be classified as follows:

1. Dynamic programming (DP)
2. Linear programming (LP)
3. Nonlinear programming (NLP)
4. Simulation

3.1.1 Dynamic Programming (DP) Models

Dynamic programming, a method formulated largely by Bellman (1957), is a procedure for optimizing a multistage decision process. DP is used extensively in the optimization of water resource systems (Buras, 1966). The popularity and success of this technique can be attributed to the fact that the nonlinear and stochastic features which are characteristic of many water resources systems can be translated into a DP formulation. Another advantage is that highly complex problems with large number of variables can be decomposed into a series of subproblems which are solved recursively.

There are numerous studies using dynamic programming and its variation to find optimal reservoir operations where flood control is a part of the operations. Buras (1965), Fitch, et.al. (1970), Hall, et.al. (1968), Young (1967), and Becker and Yeh (1974) have used conventional DP to determine optimum reservoir operation for a deterministic sequence of inflows. Beard and Chang (1979) describe stochastic dynamic programming techniques to derive flood control reservoir operation rules that minimize expected damages that are functions of the maximum outflow rate, the amount of flood-warning time and the duration of flooding.

Variations on DP include incremental DP (IDP), discrete differential DP (DDDP), stochastic DP, and differential DP (DDP).

3.1.2 Linear Programming (LP) Models

LP has been one of the most widely used techniques in water resources management. It is concerned with solving a special type of problem: one in which all relations among the variables are linear, both in constraints and in the objective function to be optimized. Although objective functions as well as some of the constraints are often nonlinear, various linerarization techniques can be used.

A typical planning objective for LP applied to a reservoir operation model is to minimize the capacity (or cost) of the reservoir while meeting all system requirements or to maximize total system net annual benefits. Cost functions must be convex and benefit functions concave for LP to be successfully used.

LP has been applied to solve water resources management problems varying from relatively simple problems of allocation of resources to complex situations of system operation and management.

Dorfman (1962) demonstrated how LP could be used with three versions of a model, increasing in complexity from a simplified river basin planning problem to a model where inflows are treated stochastically. Hall and Shepard (1967) developed a DP-LP technique for a reservoir optimization problem. Windsor (1973) developed a methodology using a recursive LP a the optimization tool for the analysis of a multi-reservoir flood control system. Becker and Yeh (1974) suggested a combined solution methodology of LP-DP for the determination of optimum real-time reservoir operations associated with the California Central Valley Project. Dalgi and Miles (1980) proposed a simple solution for four reservoirs in series for which the annual total head of water is maximized.

Variations on the basic LP model include chance-constrained LP, stochastic LP models, and stochastic programming with recourse. Some difficulties in application of these variations have been noted (Yeh,1985).

The main advantages of LP include (1) its ability to easily accommodate relatively high dimensionality, (2) a guarantee of a global optima, and (3) the availability of standard LP package computer codes.

3.1.3 Nonlinear Programming (NLP) Models

Nonlinear programming (NLP) is not as popular as LP and DP procedures in water resources systems analysis. The disadvantages are that the optimization process is generally slow and requires large amounts of computer resources. The mathematics involved is much more complicated than in the linear case, and NLP, unlike DP cannot easily accommodate the stochastic nature of inputs to the system.

NLP does provide, however, a more general mathematical formulation and may provide a foundation for analysis by other methods. NLP can effectively handle a nonseparable objective function and nonlinear constraints which many programming techniques cannot. NLP includes quadratic programming, geometric programming, and separable programming. NLP will gain its practical importance in water resources systems analysis with the development of computer technology and effective algorithms for large-scale, multi-objective optimization (Cohon and Marks, 1975; Haimes,1977).

3.1.4 Simulation Models

Simulation is a modeling technique that is used to approximate the behavior of a system on a computer, representing all the characteristics of the system largely by a mathematical or algebraic description (Maass, et al.,1962). It is different from a mathematical programming technique. Mathematical programming techniques find an optimum decision for system operation meeting all system constraints while maximizing or minimizing some objective. Alternately, the simulation model provides the response of the system for certain inputs, which include decision rules, so that it enables a decision maker to examine the consequences of various scenarios of an existing or proposed system. A simulation model is generally more flexible and versatile in simulating the response of the system than a mathematical programming model which usually requires assumptions on model structure and system constraints. Optimization implicitly examines all possible decision alternatives while simulation is limited to a finite number of input decision alternatives. In the water resources planning field, we are in fact selecting between discrete alternatives. This is one of the main disadvantages of most optimization models.

A typical simulation model for a water resources system is simply a model that simulates the interval-by-interval operation of the system with specified inflows at all locations (control points) during each interval, specified system characteristics and specified operation rules (Beard, 1972). It is quite common today to find simulation models with one or more optimization routines to perform certain degrees of optimization. Eichert (1979) pointed out that from the practitioner's point of view, mathematical programming techniques have, thus far, not proven to be widely useful because of the complexities of water resources systems and noncommensurable objectives in water resources management. In this regard, simulation is an effective tool for studying the operation of the complex water resource system incorporating the experience and judgement of the planner or engineer into the model. It would be desirable if the simulation model had some degree of self-optimization to reduce the amount of computation to obtain an optimum or near optimum operation plan for a complex reservoir system.

Several system formulation strategies were described by Eichert and Davis (1976) that use system analysis techniques to select the optimal plan from simulation model results. Since seldom will the optimum economic system be selected as best, an acceptable strategy need not make the absolute guarantee of economic optimum. The formulation strategies described are: the reasoned thought strategy where reasonable alternative systems are "reasoned" out by judgement and other criteria; the first added strategy and the last added strategy. The strategy recommended is an incremental first-added approach; that is, each new component of the proposed system is added to the existing base system and simulated without any of the other proposed components. The size of each new component is varied to determine the most cost-effective size within its constraints. The most cost-effective component is then selected for inclusion in the system, thus creating a new base system. The procedure is then repeated with the remaining candidate components analyzed in the first-added manner. The most cost-effective project is again selected and the procedure continues. Although this process does not evaluate the benefits of all combinations of projects, it results in the best incrementally justified system.

Another approach (a last-added strategy) is recommended as a means of analyzing a proposed system in which all components are assumed to be justified. The last-added strategy begins with all previously selected projects which had positive net benefits included in the plan and the system is simulated deleting one component at a time. The component which causes the net benefits to increase the most is then removed from the system. The procedure is continued until the removal of a project causes a decrease in net benefits. This strategy operated independently of the first-added approach has a drawback in that the group of projects may include components that are not incrementally justified. In all cases the system performance is assumed to be evaluated by traditional methods that make use of HEC-5 (HEC, 1985). Each of these strategies was shown to have one or more shortcomings.

3.1.5 Simulation Using HEC Programs

The Hydrologic Engineering Center has developed a package of hydrologic and economic computer programs which provide flood damage analysis for an entire range of structural and nonstructural flood plain management measures. The Flood Damage Analysis Package (HEC,1986), presently includes three computer programs to provide hydrologic and hydraulic analyses, three programs for flood damage economic evaluation, the HEC Data Storage System (HEC, 1983) for efficient manipulation and transfer of data and three programs to aid in input data preparation and data editing. Table 1 lists some typical flood-damage-mitigation measures and associated programs used for evaluation of the modifications due to each.

Table 1

HEC programs for Evaluation of Flood-Damage-Mitigation Measures

(Taken from Training Document No. 23, HEC, 1986)

	Function Modified		
Measure	**Stage-Flow**	**Stage-Damage**	**Flow-Frequency**
Reservoir	no change	no change	HEC-1,HEC-5
Levee/Floodwall	HEC-2	SID, DAMCAL	HEC-1,HEC-5[1]
Channel Modification	HEC-2	no change	HEC-1,HEC-5[1]
Diversion	no change	no change	HEC-1,HEC-5
Flood Forecasting	no change	no change	HEC-1,HEC-5[2]
Flood Proofing	no change	SID,DAMCAL	no change
Relocation	no change	SID,DAMCAL	no change
Flood Warning	no change	SID,DAMCAL	no change
Land-use Control	no change	SID,DAMCAL	HEC-1,HEC-5

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[1] Due to potential loss of floodplain storage

[2] Due to improved reservoir operation with forecast

3.1.5.1 Hydrologic/Hydraulic Analysis Computer Programs

HEC-1 Flood Hydrograph Package

The main purpose of the HEC-1 Flood Hydrograph Package (HEC, 1985) is to simulate the hydrologic processes during flood events. The Corps of Engineers uses this model as a basic tool for determining runoff from various historical and synthetic (design) storms in planning flood control measures. HEC-1 has several major capabilities which are used in the analysis of flood control measures. Those capabilities include the following:

1. Computation of modified frequency curves and expected annual damages for any location in the stream system.
2. Computation of modified frequency curves and expected annual damages for a number of different plans in the watershed in a single computer run (multiplan option).
3. Optimization of flood control system components (levee, reservoir, pump, or diversion).

HEC-1 aids in flood control planning analysis in two ways. First, given a set of measures constituting a plan, the program can determine the optimal size of each of the components based on maximizing net benefits. Second, given a number of discrete plans, the hydrologic impact of each flood control scheme can be computed in a single run.

The main purpose of HEC-1 for use in flood-damage analysis is to develop existing condition and modified condition flow-frequency curves for input to the branch-and-bound program. Although HEC-1 includes detention structures as a flood control measure, the program does not simulate the operation of reservoirs. There is currently no provision in HEC-1 to select the combination of measures at sites to yield the optimal flood control plan.

HEC-2 Water Surface Profiles

HEC-2 (HEC, 1982) computes steady-state, gradually varied flow water surface profiles for specified flows in natural or man-made channels. In flood analyses studies, it is used to develop stage-flow rating curves. The principal use of the HEC-2 program has been in determining inundated areas associated with various flood flows. The simulated area and depth information is used by the Corps to evaluate flood damages. HEC-2 can analyze the impact of channel improvements and levees on water surface elevations through flood prone areas. The modified stage-flow functions can be written to the DSS file during an HEC-2 run where it can later be combined with the stage-damage and flow-frequency functions in EAD. The expected annual damage reduction resulting from a channel improvement can thus be computed.

HEC-5 Simulation of Flood Control and Conservation Systems

The HEC-5 program (HEC, 1982) was designed to simulate the operation of multipurpose water resource systems consisting of reservoirs, points of demands or controls (control points), and interconnecting channels. HEC-5 is the basic simulation model used with the branch-and-bound optimization routine. It is used to simulate complex systems of reservoirs to meet numerous flood control, water supply, hydropower, and instream requirements. Operation is accomplished by specifying demands at the reservoir and at any downstream control points desired. The flood control capabilities include analysis of structural and nonstructural measures formulated to reduce flood damages (Eichert, 1985). The structural aspects of flood control modeled by HEC-5 include reservoirs, levees, diversions, and channel improvements which reduce the river flood flow rates and/or stages. Nonstructural measures are those which are designed to protect specific properties such as raising a structure, flood proofing, flood forecasting, and removal of damageable property. Nonstructural measures are represented in HEC-5 by changes in the flow- or stage-damage relationship.

Expected annual damages can also be computed by HEC-5, as with HEC-1. When costs of proposed reservoirs and channel improvements are given, the net benefit for a given plan can be computed with HEC-5.

The investigation of flood control system components with HEC-5 is done on a trial-and-error basis. For each alternative plan, the system is simulated with HEC-5, and the system net benefits compared. There is currently no algorithm within HEC-5 to determine automatically the optimal combination of components. However, the systematic methodology described previously in Section 3.1.4, can greatly decrease the number of trials for systems of more than a few components.

3.1.5.2 Flood Damage Analysis Programs

EAD (Expected Annual Damage Computation)

The EAD program was developed to assist in the economic analysis (specifically, damage reduction), of flood-damage-mitigation plans. This program is based on the principle that flood damage to an individual structure, group of structures of floodplain reach can be estimated by determining the dollar value of flood damage for different magnitudes of flooding and by estimating the percent chance exceedence of each flood magnitude. Damage may be computed by : (1) evaluation of damage associated with a specific event; (2) expected annual damage values associated with a specific year or several selected years, and (3) the equivalent annual flood damage associated with a specific discount rate and period of analysis. The concept of "equivalent annual value" allows direct comparison of alternative plans or comparison of damages with costs. The equivalent annual value represents a uniform distribution (the same each year) of annual values and is computed by discounting and amortizing each year's expected annual damage value over a period of analysis. The discounting and amortization takes into account the time value of money associated with damage values.

The input data for EAD consists of floodplain management plans, damage reaches, damage categories, flow-frequency or stage-frequency relationships, rating curves, stage-damage relationships, year identification of the input damage and/or costs and identification of base condition years. Computations are based on inputs of hydrologic (flow-frequency), hydraulic (stage-flow), and flood damage (stage-damage) data associated with each damage category and reach. HEC-1, HEC-2, HEC-5, DAMCAL and SID programs provide various aspects of this information.

The principal reason for computing flood damage is to determine the effectiveness of different flood damage mitigation plans in reducing damage. This reduction is commonly referred to as an inundation reduction benefit and is measured as the difference in equivalent annual flood damage with and without a plan. Different flood-damage-mitigation plans alter the stage, flow frequency and/or damage relationships in different ways. For any plan which causes a change which can be quantified, damage with the plan can be computed and damage reduction benefits between alternative plans can be compared.

DAMCAL (Damage Reach Stage-Damage Calculation)

The DAMCAL program (HEC, 1979) computes the stage-damage relationship for specified segments of the floodplain called damage reaches. The stage-damage relationships are then used by other programs (HEC-1, HEC-5, and EAD) to compute flood damages for specific events and on an expected annual basis. Nonstructural measures such as land use control, flood proofing and raising structures can be evaluated with DAMCAL.

SID (Structure Inventory for Damage Analysis).

The SID program (HEC, 1982) processes inventories of structures located in the floodplain. Its primary use is to develop stage-damage relationships. The SIDEDT program (HEC, 1982) is used to edit structure inventory and damage function files used for the SID program.

3.1.5.3 Data Management Programs (DSS, DSSUTL, DSPLAY, and PIP)

HECDSS (HEC, 1985) was developed by the HEC to store time series and paired function data. DSS is a collection of subroutines that can be called by application programs (such as HEC-5 or EAD). The programs retrieve from the DSS software or pass to the DSS software various data and associated descriptors. The DSS program can then access a file and either retrieve or store data in that file. In addition to the applications programs, a family of utility programs (DSPLAY, DSSUTL,and PIP) can be used to access the data and perform various functions, such as tabulation or plotting data. Appendix A contains a more detailed description of the Data Storage System.

3.2 Branch-and-Bound Applications in Water Resources Planning

The general features of branch-and-bound methods and applications have been presented in the management-science and operations-research literature. Mitten (1970) describes a general theoretical framework for branch-and-bound methods and formulates, in general terms, the conditions for the branching and bounding functions. The concepts developed are illustrated in an application to discrete programming. Discrete programming, which includes integer programming, combinatorial optimization problems and others, has provided much of the impetus, Mitten observes, for the development of branch-and-bound methods. Lawler and Wood (1966) present a survey of branch-and-bound methods and describe specific applications to integer programming, nonlinear programming, the traveling-salesman problem, and the quadratic assignment problem and to non-mathematical programming problems.

Applications of branch-and-bound methods in water resources planning have been concerned with problems of selecting, sizing, sequencing and scheduling projects. Brill and Nakamura (1978, 1979) present a branch-and-bound method to generate systematically attractive alternative plans for regional wastewater treatment systems and to evaluate economic trade-offs among alternative plans. This single objective branch-and-bound method proposed by Brill and Nakamura was extended by Nakamura and Riley (1981) to include analysis of multi-objective fixed charge network flow problems which are commonly found in water resources planning situations. The method was applied to the problem of locating and sizing of a regional wastewater treatment system. A FORTRAN program was used to analyze the example problem. Morin (1975) suggested the use of implicit enumeration by branch-and-bound algorithms for the solution of the combinatorial optimization problems of project sequencing encountered in the planning of large scale water resources systems. The work of Harris (1970) describes how general planning processes can be viewed in terms of branch-and-bound processes.

Windsor (1975) presents a methodology using mixed integer programming as the optimization tool for the planning and design of multi-reservoir flood control systems. His programming model allows variation in reservoir location, capacity and operating policy in selecting a cost-effective flood control system. He assumes that the reservoir release in any time period is limited only by the spillway capacity. In situations in which the flow is uncontrolled, that is, dependent only upon the current storage volume, the addition of rather complex piecewise linear constraints is required. Other significant limitations of this work are the consideration of only single-purpose reservoirs as the flood control measures.

Nonstructural floodplain alternatives, such as zoning plans, were examined as flood damage reduction measures by Bialas and Loucks (1978). A general nonlinear mathematical programming model is proposed as an analytical screening technique. The technique identifies those plans most worthy of a more detailed analysis using more precise simulation models. This preliminary evaluation of alternative floodplain zoning policies was shown as an example problem to illustrate some of the features of the model. The management (model) objective described was the maximization of location rent derived from land use allocations minus the annual expected flood damage and the annualized relocation costs. The model assumes a relationship between the probabilities that specified areas in the river basin are flooded and the cost of structures that achieve these probabilities.

Ball, Bialas, and Loucks (1978) propose a branch-and-bound optimization routine to evaluate alternative capacities and locations of various flood control structures required to protect a floodplain from a specified design flood. The algorithm is used to estimate the least-cost solution required to protect specified land areas from a specified flood event. A broad range of structural flood control options is allowed as well as almost any reasonable reservoir operating policy.

Ford (1986) describes a branch-and-bound procedure for selecting the optimal combination of flood-damage-mitigation measures and illustrates how the HEC programs can be used in the analysis. To account for the risk of a range of flood events, a statistical analysis technique in the form of expected value analysis is used to compute the net benefit of any specified flood-damage-mitigation plan. The objective function is stated as:

$$\textbf{Maximize net benefit} = E[DB] - E[DP(P)] + E[OB(P)] - E[C(P)] \qquad \textbf{(Equation 1)}$$

in which E[ ] denotes the expected value of the argument; DB = base condition total-catchment inundation damages; DP(P) = total catchment inundation damages with plan P implemented; OB(P) = other benefits of plan P; and C(P) = total cost of plan P. The goal of plan formulation is to identify the plan P, which yields the maximum value to the objective function.

The procedure presented subsequently in this paper is based on that work, with modifications to the algorithm to analyze various reservoir operating policies and storage allocation trade-offs between flood control and water supply purposes. The algorithm constitutes the basis of the branch-and-bound program.

3.3 Branch-and-Bound General Description

Branch-and-bound methods are enumerative schemes for solving optimization problems while only a fraction of the solutions are explicitly enumerated. In the water resources planning field, many alternatives are commonly proposed to solve a specific problem. To analyze each alternative is costly in both time and money. Branch-and-bound methods eliminate the need to identify every possible solution. This is accomplished through two basic operations:

1. Branching, or dividing the entire set of solutions into subsets, and
2. Bounding, which consists of establishing the upper bound on the value of the net benefit achievable with any subset plans defined in the branching procedure. The subset bound is a partial objective function which includes only the costs and benefits down to the last site in the subset, subtracted from base condition damages for all sites. An upper limit on all plans which include those measures is thus established.

Branch-and-bound enumeration is particularly applicable to the problem of identifying the optimal flood control plan for several other reasons. The first reason as previously mentioned is that the great number of alternative plans possible in a very complex or large system is costly and time-consuming to analyze. Branch-and-bound enumeration systematically analyzes combinations of measures and eliminates the need to analyze each possible plan. In many flood control planning situations, it may not even be clear what combination of measures exist. Secondly, flood control planning typically involves discrete decision variables and plan selection between discrete alternatives for which finding an optimal solution are similar to those of integer programming procedures. Branch-and-bound algorithms are a general class of methods of finding an optimum of a very large number of discrete points (or alternative plans). Third, planning intrinsically involves interaction of decision variables. In multi-site water resources development, sets of measures are generally either mutually reinforcing or mutually incompatible. Branch-and-bound efficiently eliminates entire subsets which are shown to be infeasible, or incompatible with other proposed measures. A fourth very useful feature of branching-and-bounding is the opportunity to compute solutions that differ from the optimum by no more than a prescribed amount. "Heuristic programming" in general terms, refers to systematic search procedures which are not guaranteed to find an optimum. The objective in constructing a heuristic procedure is to achieve an optimal balance between the savings in the cost of the search and the closeness of the approach to optimality. Branch-and-bound enumeration is a mathematical programming procedure which, in sufficient time, guarantees a global optimal solution. However, because the general procedure does not specify a good means for solving any particular problem, an understanding of the problem itself is required. Suppose for example, it is decided at the beginning that a feasible solution whose net benefit is no more than 10 percent less than that of the optimal solution would be acceptable. Then, if a feasible solution is found with net benefits of 100, all plans with bounds of 90 or less can be eliminated (1.10 x 90 = 99 < 100). The utility of this feature in flood control planning studies is as a screening rather than selection tool. More detailed hydrologic and hydraulic analysis may be performed on those plans passing the screening, then the branch-and-bound procedure may be used to identify the optimal plan.

Sometimes, other aspects of a flood-damage-mitigation plan, such as environmental or social requirements, must be considered along with the economic objective in final plan selection. A fifth feature of the branch-and-bound procedure is the ability to express these other considerations as constraints in the plan formulation problem. Constraints which are quantifiable but do not create an infeasible plan, can be treated analytically in the branch-and-bound algorithm by imposing a penalty on the net benefit (by either increasing the cost or reducing the damage reduction benefit). Constraints which must always be satisfied can be treated by assigning a very high cost to all plans which violate that constraint, thus insuring no such plan will be selected.

3.4 Branch-and-Bound Procedure

A step-by-step procedure for identifying the optimal flood-damage-mitigation plan is given by Ford (1986). The procedure begins by dividing the set of all possible plans into mutually-exclusive subsets for evaluation. Subdivision is made on the basis of project site, beginning at the most upstream site in the drainage basin and proceeding downstream. A site is defined in this context as a location at which alternative flood-damage-reduction measures have been proposed for implementation. These measures are mutually exclusive, that is, one and only one of the proposed alternative measures will be selected at each site to constitute the optimal plan. A damage center must be located downstream of each site to permit evaluation of incremental benefits with the EAD program. However, the branch-and-bound algorithm passes only information about those sites with damage locations to EAD for economic analysis. Thus, sites with no associated downstream damages may be included in the HEC-5 system simulation. The EAD input file will contain only those sites with damage centers.

In the branch-and-bound process, subsets are divided as needed until the optimal plan is identified. The objective function as stated in equation 1 is used to compute the net benefit of any plan in the branch-and-bound procedure. In equation 1, E[DB] is the expected value of the base condition damages for all sites in the basin. The expected value of damage with plan P implemented is also called the residual damage term, E[DP(P)]. This term includes the damage reduction for all measures acting individually and synergistically (as a system). The benefit term, OB(P) also includes individual cost of measures plus any additional cost required to implement the plan as a system.

Equation 1 is also used to compute the upper bound of the net benefit achievable with any subset of plans defined in the branching procedure. The subset bound is a partial objective function which includes only the costs and benefits of measures known with certainty to be in the subset. These costs and benefits are summed down to the last site in the subset and are subtracted from the base condition damages for all sites, thus becoming an upper limit possible on all plans which include those measures. Any measure included for sites further downstream will always reduce this total.

Computation of the bound allows elimination of subsets that cannot possibly include the optimal plan. This is the goal of the branch-and-bound procedure. If a subset bound is less than the net benefit achievable with any trial optimum plan, the subset cannot contain a better plan. The value of the subset bound cannot increase as the subset is further divided so the bound (net benefit) cannot increase. This subset can then be eliminated and another considered. Another feature of the branch-and-bound method is that of backtracking. The algorithm uses a simple backtracking procedure to explore new solutions. In the backtracking step, the next option at the previous site is reconsidered when all measures have been analyzed at a downstream site. The efficiency of backtracking enables partial solutions to be generated and evaluated very quickly.

The step-by-step procedure is shown schematically in Figure 2 and described in the following paragraphs.

a. **Initialize.** The first step is to set the initial trial optimum as -999. For evaluation of the subset bound, set a site pointer S=1.

b. **Evaluate Objective Function.** The objective function is then computed for the status quo plan (the status quo plan is the first measure at each site.)

c. **Compare.** If the trial optimum exceeds the objective function, evaluate the subset bound (step d) If not, a better plan is identified. Set the new trial objective function to this plan's trial optimum and evaluate the subset bound (step d).

d. **Evaluate Subset Bound.** Compute the subset bound for site S. If the trial optimum is greater than the subset bound, eliminate this subset, then modify plan (step e). If the trial optimum is greater than the subset bound, consider the next downstream site (set S=S+1). If this is the last site modify plan (step e). If this is not the last site, evaluate the subset bound again. Continue this process until the trial optimum is greater than the current subset bound or the last site in the system has been reached.

e. **Modify Plan.** If all measures for site S have been considered, begin backtrack procedure (step f) If all measures have not been considered, replace current measure for site S with the next measure and check for complete plan (step g).

f. **Backtrack.** Eliminate measure for site S. Move back upstream (set S=S-1). If S=0, terminate. If S=O, modify plan (step e).

g. **Check for Complete Plan.** If plan is complete, evaluate system constraints (step h). If plan is not complete, go to the next site and add the first measure. Continue until a complete plan is formulated.

h. **Evaluate Constraints.** If system requirements are satisfied, evaluate the objective function (step b). If not, modify plan (step e).

The entire process is repeated to identify the optimal flood-damage-mitigation plan. The number of iterations depends upon the number of sites in the system, the number of proposed measures at each site and the order in which the alternative measures are evaluated. In most cases, the procedure requires evaluation of only a fraction of the total number of possible plans.

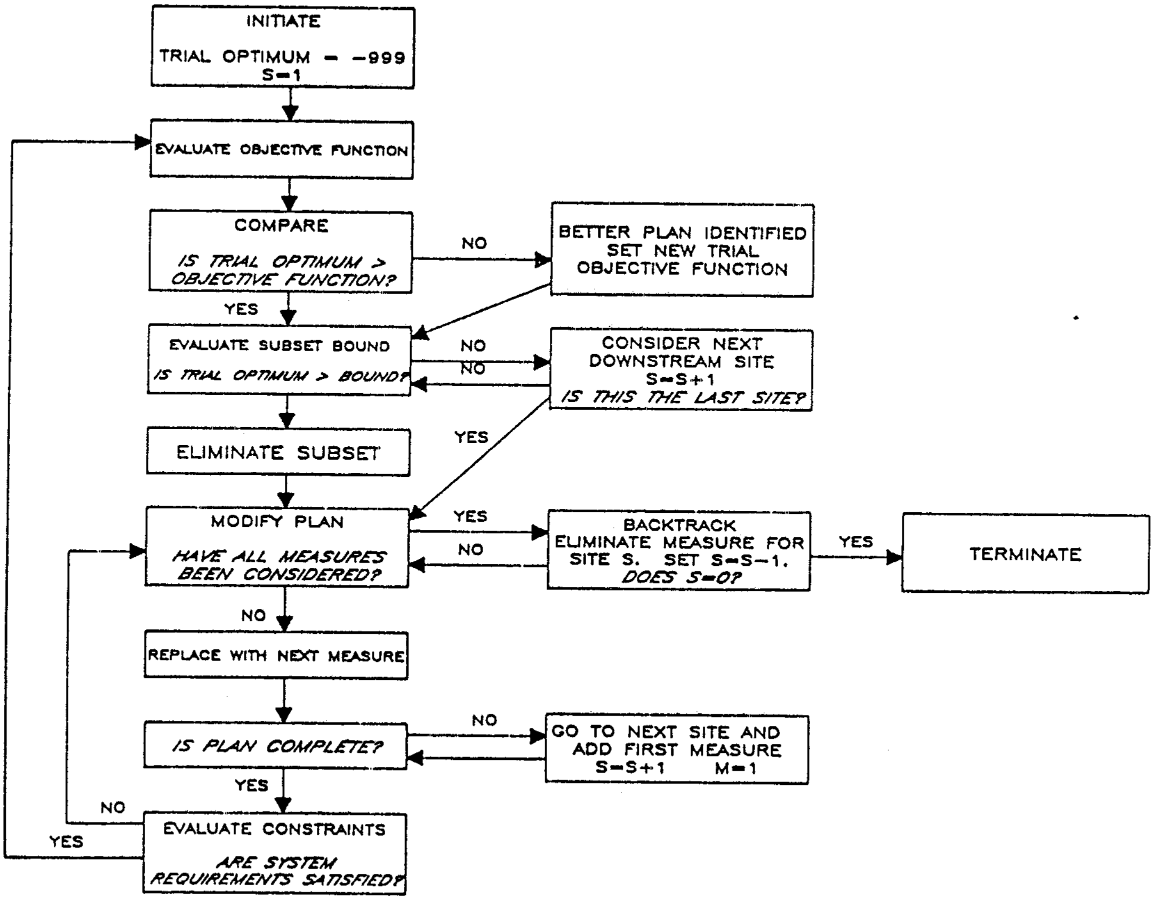

Figure 2
Branch-and-Bound Algorithm

Chapter 4

Plan Selection Using the Branch-and-Bound Algorithm in Conjunction with HEC-5 and EAD

4.1 General Approach

The general approach taken is to identify the optimal flood-damage-mitigation plan using the branch-and-bound procedure in conjunction with HEC programs required to perform the hydrologic, hydraulic and economic analysis of the measures. For efficiency, data are transferred between programs through DSS files. A schematic showing the link between existing HEC programs, new routines, and input data files is given on Figure 3.

Several computer software components were developed to accomplish the branch-and-bound plan selection. The new routines were developed on a Harris 1000 virtual memory minicomputer with 2 megabytes of memory. The software was written in ANSI standard FORTRAN 77. The branch-and-bound program requires that HEC-5, EAD, DSS and any other programs used to input data into the DSS file should all exist on a single computer system so that programs and files can be called by the branch-and-bound routine in a straightforward manner. The programs must be the proper versions; they must contain the DSS system software calls to be able to write and read data from the DSS files. The EAD version must be at least September 1986, when capabilities were added to allow data to be written to a DSS file and to allow all six types of paired data to be read from a DSS file.

Three primary HEC programs are used. Their functions in the branch-and-bound procedure are the following:

1. **HEC-5** is the basic model used to describe existing conditions in the basin and the hydrologic and economic parameters of all the proposed measures at each of the sites. Input to the branch-and-bound program is based on the standard HEC-5 input, with two additional records needed to delineate proposed measures. The branch-and-bound main routine controls the measures that are included in the input data at any one time. HEC-5 is used to compute the flow hydrographs throughout a basin for plans in which reservoirs modify the flood, thus yielding information required to develop a flow-frequency function for modified conditions. Existing condition flow-frequency functions can be derived using various techniques. Typically, a statistical analysis is performed on historic streamflow records to determine the exceedence-frequency of various magnitudes of annual peak flow. These existing condition flow-frequency functions are also written to the DSS file for later use with EAD. HEC-5 is called by the main routine to compute the modified relationship for every plan in which a reservoir or diversion is proposed or operation criteria changed at an existing reservoir in the basin. Damage data corresponding to flows is written from the HEC-5 input format into the DSS file and used by EAD in the economic analysis.

2. **EAD** is used to compute the expected annual damage for both base condition damages and damages with each proposed plan in effect. A base condition EAD input file is created which accesses base condition flow-frequency data already in the DSS file (written by HEC-5). The main routine controls the measures in the current plan and the corresponding relationships, which are modified as a result of the plan. Net benefits of the plan are then

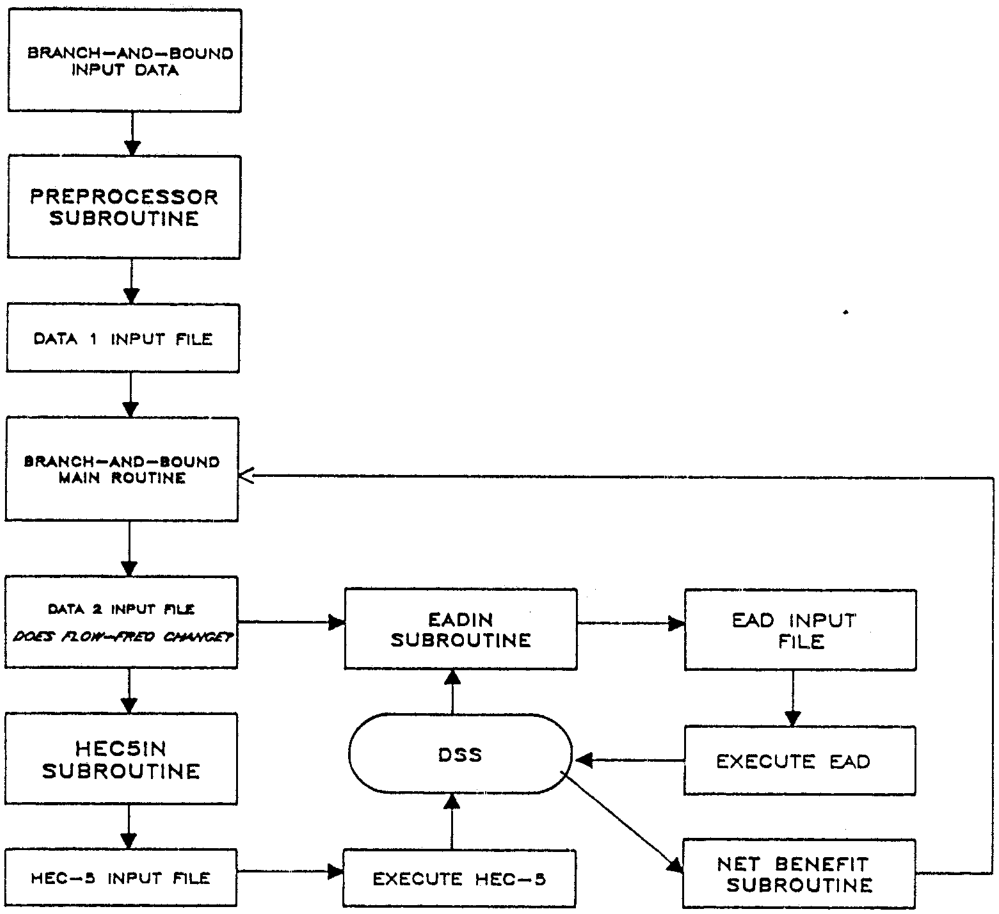

Figure 3
Branch-and-Bound Link to Other Programs

computed in subroutine NETBEN by subtracting costs of all measures included in the plan from the inundation reduction benefit (equation 1). Subset bounds are computed in a similar fashion; however, only costs and benefits sure to be in the subset are included in equation 1.

This process of generating an EAD input file, computing the net benefit, comparing to the trial optimum in the branch-and-bound algorithm and generating a new plan and EAD input file continues until an optimal plan is identified.

3. The Data Storage System **(DSS)** is the data exchange link between other HEC programs used to analyze various aspects of the flooding problem. DSS path-naming conventions are described in detail in Appendix A.

The HEC-5 program accepts and uses flow-frequency and flow-damage functions. Base conditions which can be given in terms of these two relationships will be read from the master input data file and written to the DSS file with the appropriate site identifier in the B-part, "BASE" as the E-part, and the appropriate type of data in the C-part. If other functions are required to describe base conditions, these must be entered into the DSS file via another means prior to program execution. Measures which alter other than the flow-frequency function must also be previously entered into the DSS file.

Several additional HEC programs may be used to perform hydrologic and hydraulic analyses required by certain measures. The computed modified function is stored in the DSS file. The pathname identifies these data by site, measure, and data type. The following programs may be used to enter this data:

> HEC-1 can be used instead of HEC-5 to define the flow-frequency function at locations in a basin for either existing or modified conditions. HEC-2 can be used to derive the stage-flow function at a location on a stream. If a measure modifies the stage-flow function and base conditions were described by flow-frequency and flow-damage relationships, the stage-damage function must also be given for this measure in order to derive the damage-frequency relationship. SID can be used to evaluate measures that modify damage susceptibility or can be used to represent existing conditions when required. PIP can be used to enter any of the six possible paired functions directly from a keyboard into a DSS file.

4.2 Results

In order to verify the results of the program, a problem with a known "true" solution is used to test the model. A data input file was prepared of the hypothetical Loucks Creek example (Ford, 1986) which is a step-by-step hand solution of the branch-and-bound procedure at a two site system. Computer model results were the same as obtained by the hand calculations.

Program output consists of a summary of the sites and measures in the system and an economic summary of the optimal plan. Intermediate results explaining the branch-and-bound process and an economic summary of all plans enumerated can also be requested. This is useful for verification of the procedure and also as an aid to determining other potentially feasible plans should the optimal plan not be selected. It should be noted that the plan yielding the second highest net economic benefit is not necessarily the second best plan. If the plan selected as the optimal plan by the branch-and bound procedure is found to unacceptable for non-economic reasons, the measure which made it unacceptable should be assigned a high cost and the branch-and-bound procedure performed again. The branching process in the recalculation may be different causing plans not previously analyzed to be enumerated and as a result a new optimal plan may be determined which was not originally the second best.

EAD and HEC-5 input files which have been saved for the optimal plan and may be executed again using standard EAD and HEC-5 job control language in order to obtain output from these programs.

4.3 Theoretical Assumptions and Limitations

A basic assumption in the branch-and-bound procedure is that the plan selected is the plan that yields the maximum net economic benefit. This single objective is consistent with the Water Resources Council's Principles and Guidelines which established the single objective in flood control plan selection as the national economic objective.

Flood-damage-reduction is considered the single purpose for all measures proposed with the exception of reservoir alternatives. Water supply purposes can be evaluated as a trade-off with flood control by adjusting both the reservoir storage level and value of water in conservation storage. For example, suppose an existing reservoir with 100 units of flood control storage would yield a flood damage reduction of x dollars. If 50 units were to be allocated to conservation storage, the flood damage reduction benefit would decrease but an additional benefit amount would accrue to the water supply yield. This can be accounted for by adjusting either the cost or benefit amount. The branch-and-bound algorithm can efficiently perform such an analysis.

As currently written, the branch-and-bound routine recognizes only one damage category.

Sizes of all proposed measures and potential operating rules at reservoir sites considered in the basin are assumed to be known or previously determined. Selection is thus made on these discrete alternative sizes and capacity optimization in-between any of these input sizes is not a capability of the program. As previously discussed, in practice, determination of final sizing of measures or final reservoir operating rules is generally a problem of selection of best of discrete alternatives.

Chapter 5

Example Problem Solution

5.1 Description of Basin Flooding Problem

The system used to demonstrate the branch-and-bound program is based on the Fall River System as described by Johnson and Davis (1975). An HEC-5 model of the Fall River System (Figure 4) is presented as HEC-5 Standard Test 10 (HEC, 1982). In its natural (unregulated) condition, flooding caused extensive flood damages in the vicinity of control point 4. To reduce damages, two reservoirs have been constructed in the basin at control points 1 and 2. Although they have been effective in reducing damages, flooding still occurs and an array of measures are being investigated to help reduce the remaining flood hazard.

A major storm which occurred 5-10 June 1952 was selected from hydrologic records to be representative of major flood events. Local inflows to the river resulting from this storm were computed at five control points (see Figure 4), using unit hydrograph techniques. The base hydrograph in the simulation was computed using average inflows for 6-hour time periods at control points 1-4. The base condition flow-frequency relationships for control point 4 were developed from hydrologic studies (Johnson and Davis, 1975). The effect of reservoir regulation on the basic curves used to compute flood damages is to modify the flow-frequency curve at all downstream control points. These modified flow-frequency functions are computed in HEC-5 using results from five simulations for a range of selected flood ratios.

The Fall River System was expanded using hypothetical data to include a second damage center and more reservoir alternatives to better illustrate the effectiveness of the algorithm. Hypothetical cost data was also added to allow computation of the net benefits of various plans. The modified Fall River System, shown in Figure 5, consists of three reservoir sites, a proposed channel improvement site and two damage centers. It is assumed that there are currently no controls in the basin and the sizes and costs of all proposed measures are given. The proposed reservoirs at site 1 and site 2 are for flood control only. A damage center is downstream of site 1, and damage reduction here is due to the measure at site 1 only. The proposed reservoir at site 3 is analyzed using two different reservoir operation policies. The total active storage of 800,000 acre-ft will be allocated in the first alternative strictly to flood control, and in the second alternative, 300,000 acre-ft will be allocated to flood control and the remaining 500,000 acre-ft to water supply. A constant diversion requirement of 5000 cfs is placed on the reservoir to cause the reservoir to drawdown in the conservation pool. In HEC-5, reservoirs are operated to meet specified constraints throughout the system, i.e., channel capacities for flood control or minimum flow requirements for water supply. The operation (release) in any particular time period depends not only upon these constraints but also on the current reservoir level. Each reservoir is given storage values for "target levels". A target level is defined as a level which specifies the allocation of storage for flood control and conservation purposes. In this example, the reservoirs have been partitioned into four levels. Level 1 is defined as the top of the inactive pool. The zone below this level is the dead storage zone, and releases cannot be made from this pool. Level 2 is the top of conservation storage. Below this level releases are made to satisfy minimum instream and diversion (water supply) requirements. If no conservation demands are made on the reservoir, releases are made to keep the reservoir exactly at the top of conservation pool. Level 3 is the top of the flood pool, and level 4 is the top of the dam. When the level of the reservoir is between 2 and 3, releases are made to attempt to draw the reservoir to the top of the conservation pool without exceeding the designated channel capacity at either the reservoir or downstream control points. The

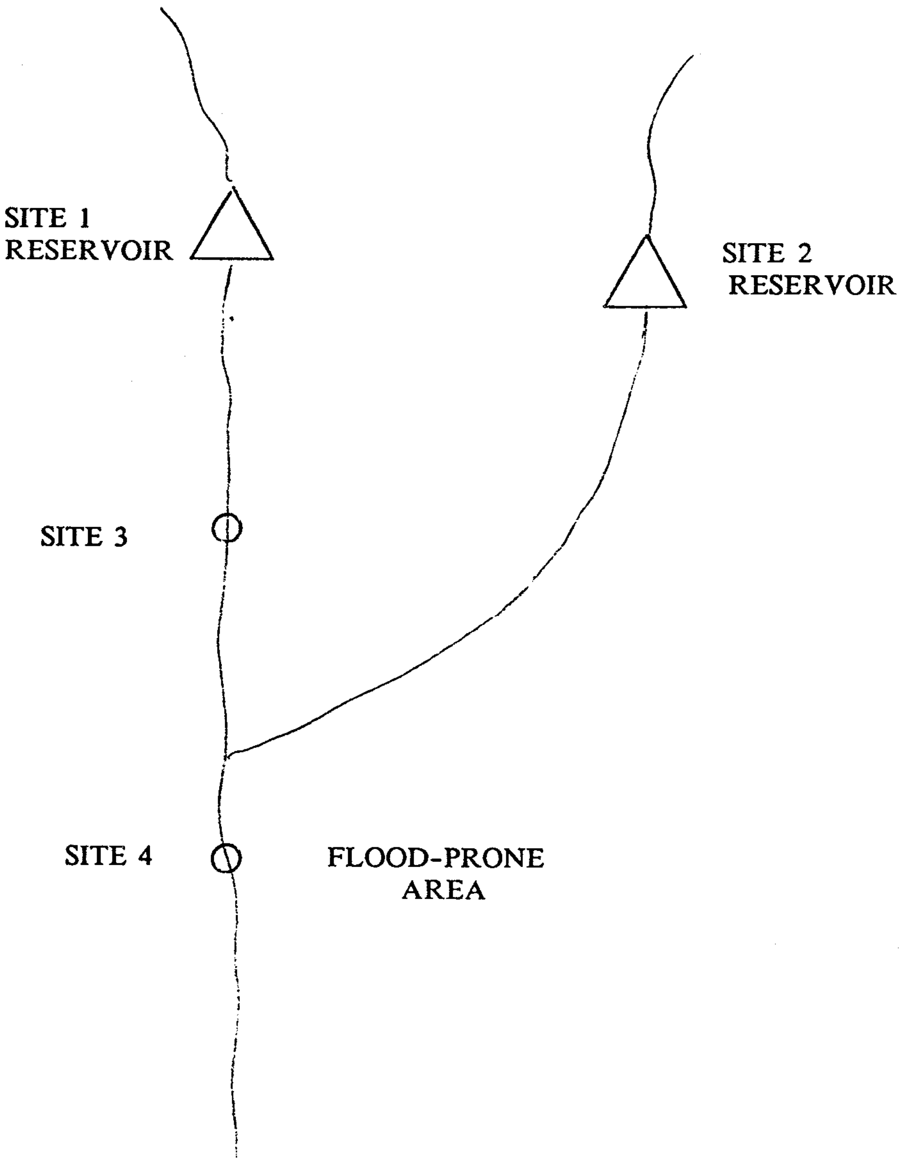

Figure 4
Fall River Existing System

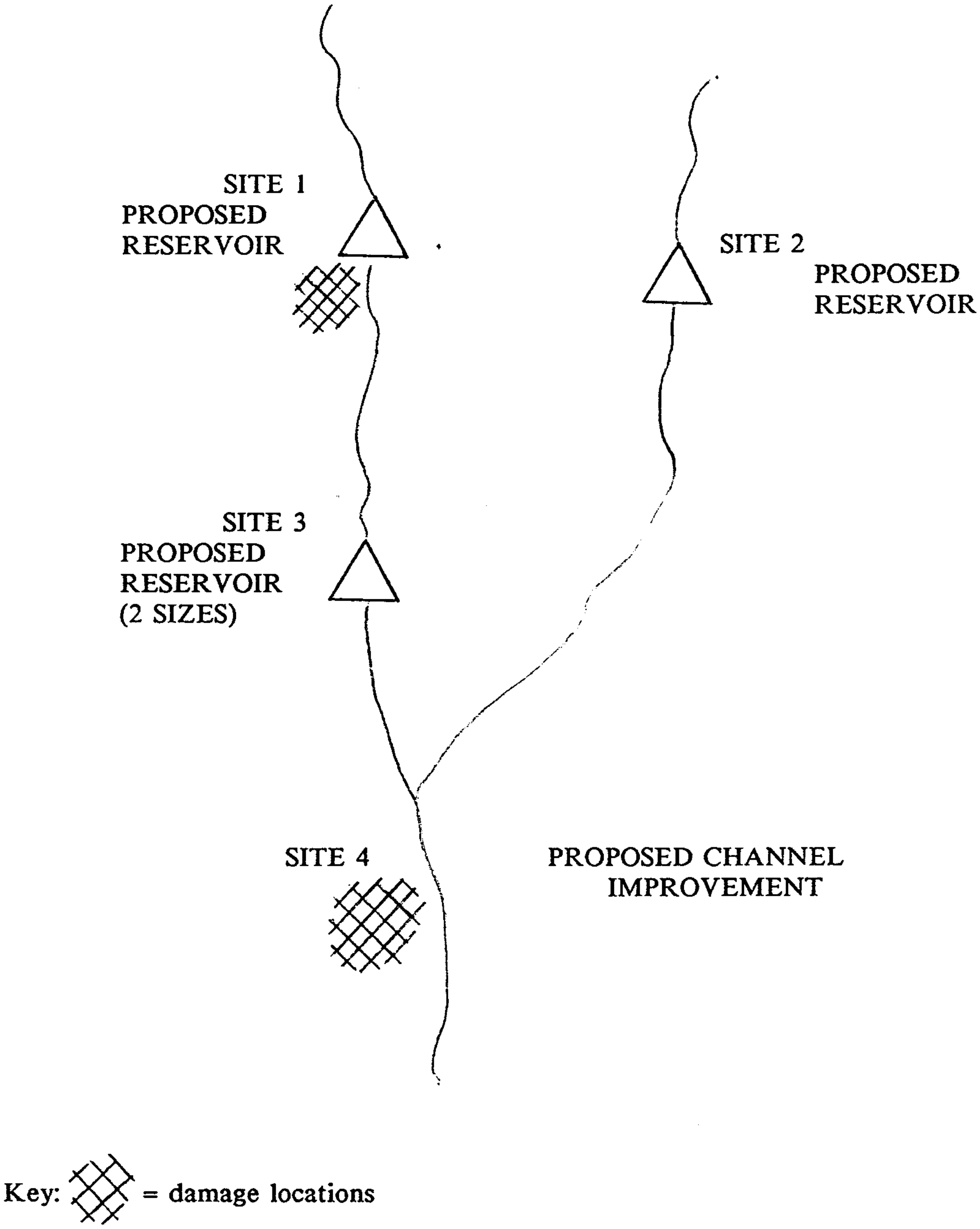

Figure 5
Fall River Basin Modified System Schematic

reservoir goes into emergency operation when the pool is above level 4. The trade-offs between water supply and flood control storage can be seen only when both a flood control channel capacity and conservation demand is given.

The cost of the reservoir at site 3 is assumed to be the cost apportioned to flood control only. The cost of one acre-ft of flood storage is assumed to be 1 unit. Therefore the alternative with 800,000 acre-ft of flood storage costs 800,000 units and the 300,000 acre-ft alternative 300,000 units. The remaining storage allocated to water supply is to be paid for by water supply benefits and is not analyzed in this model.

The final site in the basin at which a flood-damage reduction measure is proposed is site 4. Site 4 may be defined as the most downstream reach in which the channel is to be improved or status quo maintained. The damage reduction downstream of site 4 is due to the combined action of all measures at sites 1, 2, 3 and 4.

5.2 Simulation/Optimization Results

Branch-and bound output for the Fall River System is shown in Appendix D. Results of the simulation/optimization show that the optimal plan consists of status quo (measure 1) at site 1, the reservoir (measure 2) at site 2, reservoir alternative B (measure 3) at site 3 and the channel improvement (measure 2) at site 4. Expected annual damages of the existing system (status quo at all sites) are 2247[1], and with the proposed plan implemented, 732. The total annual cost is 725 for a system net benefit of 790. The optimal plan is shown to significantly reduce damages at site 4 through measures at sites 2, 3, and 4. The reservoir proposed at site 1 is shown to be economically infeasible in reducing damages at sites 1 and 4. Damages downstream of site 1 are only affected by the measure at site 1 and are therefore not impacted by the selected plan.

5.3 Effectiveness of Algorithm

During the branch-and-bound evaluation, the set of flood-damage-mitigation plans is subdivided based on the site at which the various measures are grouped. Beginning at the most upstream site, the set of all plans is initially divided into the following subsets (first level subdivision):

1. A subset that includes all plans with the status quo (measure 1) for site 1; and

2. A subset that includes all plans with the reservoir (measure 2) for site 1.

This subdivision of plans is shown conceptually in Figure 6. These two subsets are divided further as needed until the optimal plan is identified. For example, the subset that includes plans with status quo for site 1 is divided into a second level with the following subsets:

1. A subset that includes plans with status quo for site 1 and status quo for site 2; and

2. A subset that includes plans with status quo for site 1 and a reservoir for site 2.

At the second level, the partial objective function of equation 1 is called a subset bound. Each subset at the level 2 subdivision is divided into three subsets for each of the three alternatives

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[1] All costs and benefits in 1000 units.

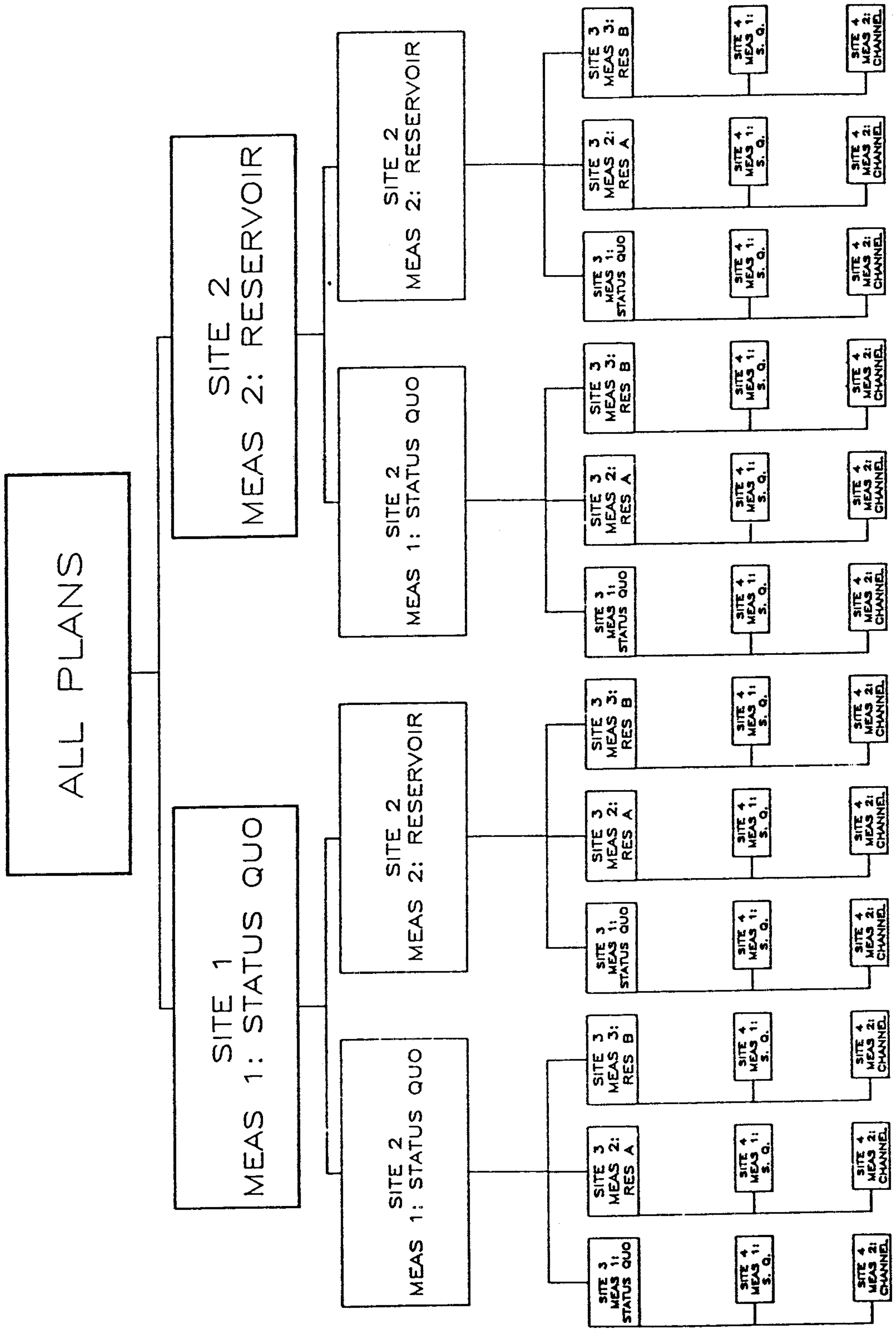

Figure 6
Subdivision of Plans for Fall River System

proposed at site 3 in a similar fashion. The fourth and last subdivision of subsets at level 3 occurs at the last site (site 4). It is at this level that subsets become plans. When each site is assigned one measure, complete plans are formulated and an objective function is evaluated.

Figure 7 illustrates the branching-and-bounding process for the Fall River example. The branching operation can be followed by the solid lines. Equation 1 is used to estimate the upper bound on the net benefit possible with any subset of plans defined in the branching operation. Only those costs and benefits of measures that are known with certainty to be in the subset are included in the subset bound. When a subset bound evaluated is less than the trial optimum, the entire subset can be eliminated from further consideration. For example, the subset bound for all plans including status quo (measure 1) for site 1, reservoir (measure 2) for site 2 and status quo (measure 1) for site 3 is 328, which is less than the current trial optimum of 710. The value of this subset bound cannot increase because all additional terms in equation 1, regardless of the measure selected at site 4, will always reduce the total. This subset is thus eliminated. The next subset including status quo (measure 1) at site 1, reservoir (measure 2) at site 2 and reservoir alternative A (measure 2) at site 3 is considered.

In this fashion, two other subsets are also eliminated, reducing the number of plans enumerated from a total possible of 24 to 16. For this example, the algorithm savings, or efficiency, is 33% (24-16/24).

5.4 Sensitivity Analysis

The efficiency of the branch-and-bound technique is sensitive not only to the feasibility of the individual measures but also to the order in which they are evaluated. To demonstrate this, in the Fall River example, the reservoir alternatives at site 3 were evaluated in reverse order. The reservoir alternative B was entered into the data before reservoir alternative A. The output is shown in Appendix E. Figure 8 shows the new branching process.

The branch-and-bound process first deviates from the first run in plan 3 and is different in every plan where measure 2 or 3 at site 3 is included in the plan. The most significant finding is that the total number of plans enumerated is reduced from 16 to 15. The initial plan, plan 11, was eliminated from evaluation because the subset bound is less than the trial optimum. The optimal plan remains the same (plan 11 in run 1 and plan 9 in run 2). The value of the objective function also remains unchanged. The optimal plan is enumerated earlier in the process in run 2. Thus, the order of input of components at each site is important to the efficiency of the algorithm, but not to the final solution.

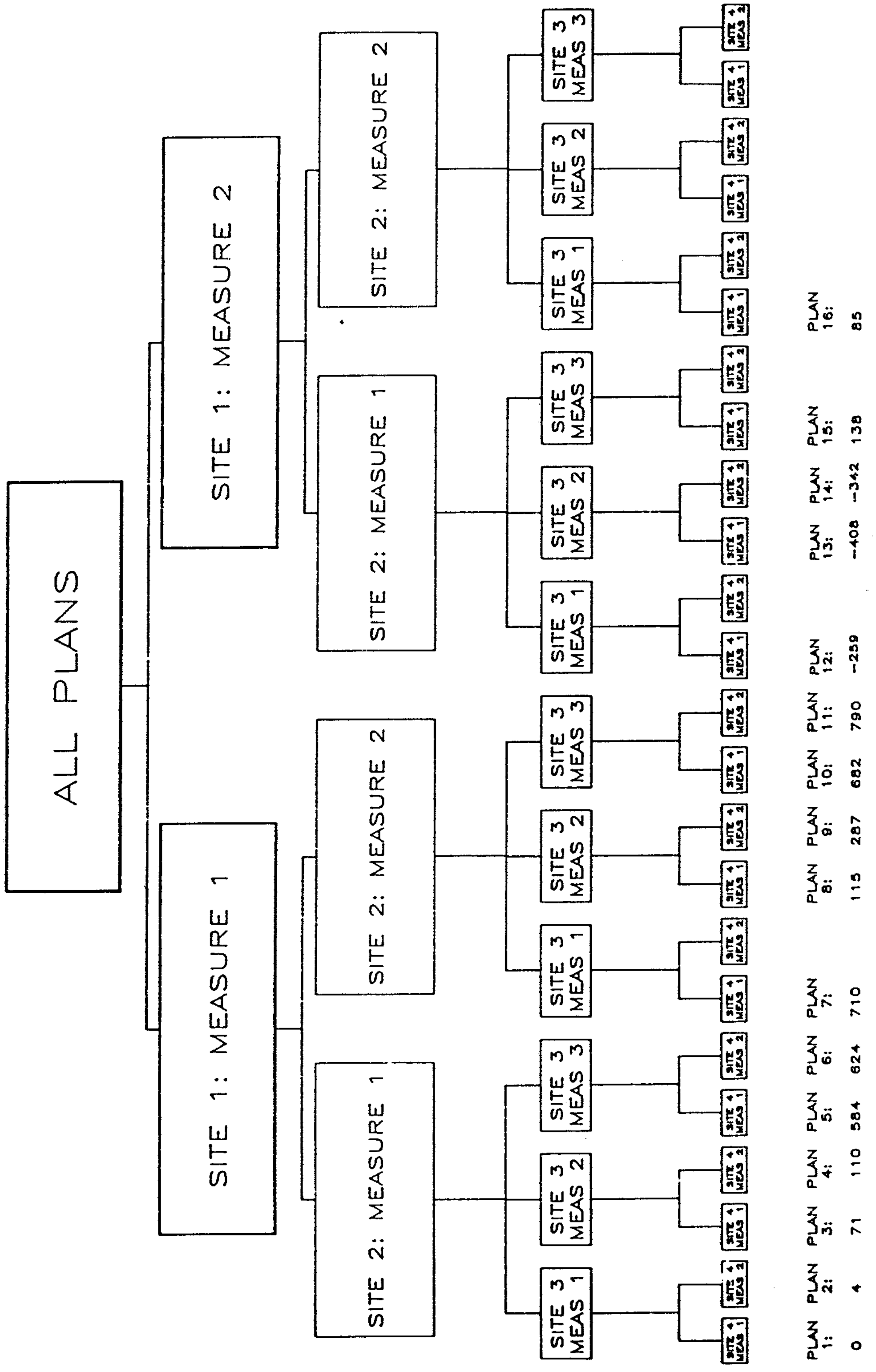

Figure 7
Branch-and-Bound Process for Fall River System

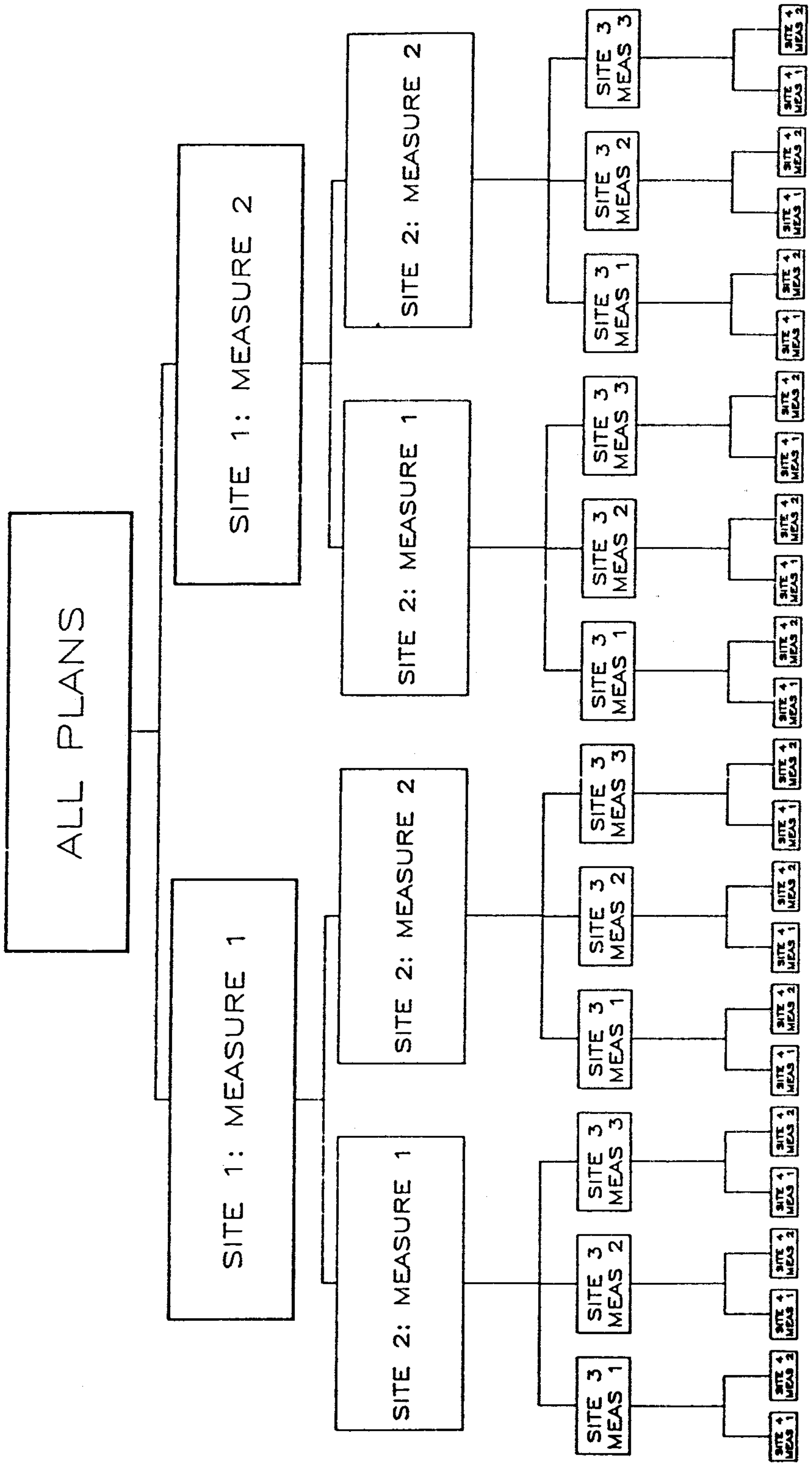

Figure 8
Branch-and-Bound Process for Sensitivity Example

Chapter 6

Recommendations for Future Work

Future work related to the branch-and-bound program can be divided into three categories:

1. Extending the program to include **new capabilities**.
2. **Linking** the program to other hydrologic analysis programs (HEC-1).
3. **Applying** the procedure in new and creative ways to simulate more complex systems.

Some specific suggestion for work in each of these areas is described in the following paragraphs:

1. **New Capabilities**. The program should allow for damage to be subdivided into the different categories currently available in EAD, and extension of the economic analysis to include calculation of annual costs from capital costs for a variety of interest rates and time periods to make full use of the economic analysis available in EAD. In general, it is recommended that the program be expanded as needed to make use of the many options available in the simulation models used to analyze the individual plans.
2. **Linking**. With a few modifications to the preprocessor program, HEC-1 can replace HEC-5 as the base model. The main advantage to linking the branch-and-bound program to HEC-1 is to allow HEC-1 users to employ this capability in planning studies without having to learn to use a new program (HEC-5). HEC-1, EAD and DSS are currently available in microcomputer versions, and the branch-and-bound program could be easily converted. If the rainfall-runoff prediction is a significant part of the study, HEC-1 may be a more suitable model. HEC-1 does not provide for the operation of reservoirs, so HEC-5 should be used when reservoir alternatives are proposed as flood-damage-mitigation measures at any site.
3. **Applying**. With some thoughtful and innovative data input preparation, the branch-and-bound program is capable of analyzing and selecting between groups of measures. For example, a sub-system of reservoirs which might be proposed collectively as one measure can be grouped together into a single site. The entire set of all possible plans then, would include either the entire sub-system or none of it.

Other aspects of reservoir operation can also be included as alternative measures. The effect of seasonal operation criteria, of flow forecasting on reservoir operation and on instream low flow requirements can all be analyzed and evaluated using the branch-and-bound program. As with the example of multipurpose reservoir operation, creative manipulation of the cost might be required to evaluate the economic trade-offs.

Chapter 7

Conclusions

The goal of flood-damage-mitigation plan selection is to identify the optimal plan (the plan that yields the maximum economic benefit). Plan selection can be performed by two general approaches:

1. Simulation models used to evaluate the economic impact of all possible plans, and comparison of results.
2. Optimization models.

Simulation models can quite accurately approximate the behavior of a system under various hydrologic and hydraulic conditions. Simulation enables a decision maker to examine the consequences of various scenarios of an existing or proposed system. In contrast, optimization models are mathematical programming techniques which find an optimum decision for system operation meeting all system constraints while maximizing or minimizing some objective. Many such techniques are proposed in the literature. The general programming techniques of LP and DP are the most common. Mathematical programming techniques have one or more of the following shortcomings:

1. They require assumptions on model structure and system constraints.
2. The hydrology and hydraulics of the system is often oversimplified.
3. They ignore planning as it is done in the real world, that of deciding between discrete alternatives.

Simulation models also have the advantage of being widely used, easy to understand, and flexible enough to analyze the impact of most flood control systems. The big disadvantage is the need to simulate the impact of all possible combinations of alternatives.

The most desirable condition is to use an optimization technique to reduce the number of simulations. This work uses a branch-and-bound enumeration algorithm to systematically select the optimal plan while using simulation models to perform the hydrologic, hydraulic and economic analysis.

Branch-and-bound enumeration is particulary applicable to the problem of flood control plan selection for several reasons:

1. Branch-and-bound enumeration systematically analyzes combinations of measures and identifies the optimal plan without having to analyze every possible combination of alternatives.
2. Branch-and-bound guarantees finding an optimum of a very large number of discrete alternatives, typical of flood control planning.

3. In multi-site water resources development, sets of measures are generally either mutually reinforcing or mutually incompatible. Branch-and-bound efficiently eliminates entire subsets which are shown to be infeasible or incompatible with other measures.
4. Branch-and bound offers the ability to screen selections that differ from the optimum by some prescribed amount.
5. Branch-and-bound allows consideration of other requirements of a flood-damage-mitigation plan as constraints by imposing a penalty on the plans that violate that constraint.

A computer model implementing the branch-and-bound algorithm was developed and linked to HEC simulation programs which perform the hydrologic, hydraulic and economic analyses. The model is developed in generalized form; thus it can be applied to most systems where flooding is occurring at one or more sites in the basin. Reservoir operation policies can also be analyzed in the context of reducing flood damages. The algorithm is shown to reduce the number of plans analyzed in a four-site system from a total possible of 24 to 16. The efficiency of the branch-and-bound algorithm is sensitive to the order in which measures are analyzed at each site. Further study to determine a method of analyzing the "best" alternative measure first, in the selection process, could improve the overall efficiency of the procedure.

The usefulness of the branch-and-bound program in conjunction with HEC-5 will be primarily to Corps districts involved in comprehensive watershed planning, especially for large or complex systems where a large number of alternative measures are proposed. Should the branch-and-bound program be implemented on a microcomputer, or linked to HEC-1, potential applications could be widespread.

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Appendix A

HEC Data Storage System (DSS)

A DSS file stores data by records. A file may contain a single record or thousands or more. A unique alphanumeric string of 80 or fewer characters identifies each record. The identifier is also called a "pathname". There is one pathname for every record and no two pathnames can be the same. The pathname begins and ends with a slash ("/") and consists of six parts, each separated by a slash ("/"). The six parts are often called A, B, C, D, E, and F. A possible pathname would be :

/A/B/C/D/E/F/

Pathname parts follow certain naming conventions as shown below:

Pathname Part	Description
A	River basin or project identifier
B	Location, reach, or gage identifier
C	Data variable or variables (eg. FLOW-FREQ)
D	Not normally used
E	Year
F	Name of alternative or measure

For example, if HEC-5 were used to compute a flow-frequency function for two alternative plans and the data were stored in a DSS file, the resulting pathnames for these functions might look like this:

/FALL RIVER/SITE1/FREQ-FLOW///BASE/
/FALL RIVER/SITE1/FREQ-FLOW///PLAN/

All functions required for computation of expected annual damage regardless of where they are generated, are passed through DSS. The following paired data and its C-pathname identifier are passed through DSS:

Basic Relationships	C-Part
Stage-Damage	ELEV-DAMAGE
Stage-Flow	ELEV-FLOW
Flow-Frequency	FREQ-FLOW

Derived Relationships	C-Part
Flow-Damage	FLOW-DAMAGE
Stage-Frequency	ELEV-FREQ
Damage-Frequency	DAMAGE-FREQ

Appendix B

Description of Branch-and-Bound Routines

The main program contains the branch-and-bound algorithm and calls six subroutines to provide various pieces of information as described below:

Subroutine PRE: Preprocessor which defines blocks of data describing single measures and stores the blocks by site and measure number.

Subroutine HEC5IN: Routine which creates an HEC-5 input file containing one measure at each site comprising a plan.

Subroutine EADIN1: Routine which creates a base condition EAD input file from user input.

Subroutine EADIN2: Routine which creates an EAD input file for a specific plan.

Subroutine NETBEN: Routine which performs the final economic net benefit analysis.

Subroutine BBOUT: Routine which writes the branch-and-bound summary output tables.

Appendix C

Input Data Overview

The master input file is based on the HEC-5 input format, and uses the same records to describe the basin characteristics, reservoir operation criteria, and system schematic. An example input file is included in this appendix. Previous experience in how to set up and use an HEC-5 data file is required in order to use the Branch-and-bound program. All the proposed measures at sites in the basin are described in the master input file.

Three new records (BB, EB and M$) are added to the standard HEC-5 input to create a master branch-and-bound input data set. Each record group describing a proposed measure begins with a "BB" record and ends with an "EB" record. The first two fields of the BB record contain the site number, beginning with 1 at the most upstream site and progressing downstream until all sites in the basin are numbered. Control points at which no measures are proposed will be input as usual. Field 2 of the BB record contains the index of the measure at that site, beginning with 1 as the status quo alternative and continuing sequentially until all measures at that site are numbered. Each alternative measure at each site is then uniquely identified by site number and measure index. The EB record is blank. The third new record is the "M$" containing the total annualized cost of the proposed measure. For existing conditions and for measures for which there is no cost (i.e., modified operating rules at existing reservoirs) the M$ record is omitted.

HEC-5 damage records (DA, DF, DQ, and DC) are required at locations where expected annual damages are to be computed. These records are written to the DSS file for use by EAD in the economic evaluation of the plan. The ZWQF record writes modified flow-frequency functions at all locations with damage records to the DSS file. ZR records containing the four required pathnames corresponding to the project, site, type of data, and measure identifier are required to define the data to be retrieved from the DSS file.

Fall River Input File

```
T1      BRANCH-AND-BOUND TEST DATA            FALL RIVER SYSTEM
T2      BASED ON HEC-5 STANDARD TEST 10
T3      THREE RESERVOIR SYSTEM - TWO FLOODING SITES
J1     0       1       4       2       3       1
J2    24       0    .167               1
J3     6                      -1               1
J4     1                                                                       2
J8  1.10    1.12    1.13    2.10    2.12    2.13    3.12    3.13    3.10    4.04
C
C
C ******************************************************************************
C                               SITE 1
C ******************************************************************************
C
C SITE 1 MEASURE 1 = EXISTING CONDITIONS
C ___________________________________________________________________
BB     1       1                                                               2
RL     1      .1      .1      .2      .3      .4
RO
RS     2      .1      .4
RQ     2      -1      -1
CP     1    6000
IDSITE01
RT     1       2      .1     1.0
EB
C
C ____________________________________________________________________
C
C SITE 1 MEASURE 2 = RESERVOIR
C ____________________________________________________________________
BB     1       2
RL     1   50000       0   50000  150832  200000
RO     1       2
RS     6       0   50000   70000  100000  150832  200000
RQ     6    5000    6500    7000    8000  100000  200000
R2 99999   99999
CP     1    6000
IDSITE01
RT     1       2      .1     1.0
M$  760.
ZR A=FORD B=SITE01 C=FREQ-FLOW F=PLAN
ZR A=FORD B=SITE04 C=FREQ-FLOW F=PLAN
EB
DA1
DF    17    .999    .900    .800    .700    .600    .500    .400    .300    .250
DF  .200    .150    .100    .050    .020    .010    .005    .002
DQ    17   28800   35000   42000   50500   60500   73000   90000  114000  130000
DQ150000  180000  230000  323000  490000  640000  840000 1000000
DC1           50      80     100     110     140     190     290     380     480
DC   600     800    1210    2200    4200    5380    6120    6500
ZR A=FORD B=SITE01 C=FREQ-FLOW F=BASE
ZR A=FORD B=SITE01 C=FLOW-DAMAGE F=BASE
C
C ******************************************************************************
C                               SITE 2
C ******************************************************************************
C
C SITE 2 MEASURE 1 = EXISTING CONDITIONS
C ____________________________________________________________________
BB     2       1
CP     2   21000
IDSITE02
RT     2       4      .1     3.1
EB
C
C ____________________________________________________________________
C
```

```
C SITE 2 MEASURE 2 = RESERVOIR
C _____________________________________________________________________
BB      2       2
RL      2  100000       0  100000  654576 1000000
RO      1       4
RS      7       0  100000  200000  400000  600000  800000 1000000
RQ      7   18000   21000   30000   40000  100000  300000  500000
R2 99999   99999
CP      2   21000
IDSITE02
RT      2       4      .1     3.1
M$  400.
ZR A=FORD B=SITE04 C=FREQ-FLOW F=PLAN
EB
C
C ****************************************************************************
C                                SITE 3
C ****************************************************************************
C
C SITE 3 MEASURE 1 = EXISTING CONDITIONS
C _____________________________________________________________________
BB      3       1
RL      3      .3      .2      .3      .4      .5
RO
RS      2      .1      .5
RQ      2      -1      -1
CP      3   12000
IDSITE03
RT      3       4      .1     3.2
EB
C
C _____________________________________________________________________
C
C SITE 3 MEASURE 2 = 800000 AC-FT FLOOD STORAGE
C _____________________________________________________________________
BB      3       2
RL      3  200000       0  100000  900000 1000000
RO      1       4
RS      7       0  100000  200000  400000  600000  800000 1000000
RQ      7   18000   21000   30000   40000  100000  300000  500000
R2 99999   99999
CP      3   12000
IDSITE03
RT      3       4      .1     3.2
DR      3                                                   5000
M$  800.
ZR A=FORD B=SITE04 C=FREQ-FLOW F=PLAN
EB
C
C _____________________________________________________________________
C
C SITE 3 MEASURE 3 = 300000 AC-FT FLOOD STORAGE
C _____________________________________________________________________
BB      3       3
RL      3  200000       0  600000  900000 1000000
RO      1       4
RS      7       0  100000  200000  400000  600000  800000 1000000
RQ      7   18000   21000   30000   40000  100000  300000  500000
R2 99999   99999
CP      3   12000
IDSITE03
RT      3       4      .1     3.2
DR      3                                                   5000
M$  300.
ZR A=FORD B=SITE04 C=FREQ-FLOW F=PLAN
EB
C
C ****************************************************************************
C                                SITE 4
C ****************************************************************************
C
C SITE 4 MEASURE 1 = EXISTING CONDITIONS
C _____________________________________________________________________
```

```
C
BB      4       1
CP      4   40000
IDSITE04
RT      4
EB
C _____________________________________________________________________
C
C SITE 4 MEASURE 2 = CHANNEL IMPROVEMENT
C _____________________________________________________________________
BB      4       2
CP      4   40000
IDSITE04
RT      4
QS      9   10000   20000   30000   40000  100000  300000  500000  700000  900000
EL      9     300     350     450     500     550     600     625     650     700
C$ 40000    2000    4000    5000    6000
M$   25.
ZR A=FORD B=SITE04 C=FLOW-DAMAGE F=PLAN
EB
DA1
DF     17    .999    .900    .800    .700    .600    .500    .400    .300    .250
DF   .200    .150    .100    .050    .020    .010    .005    .002
DQ     17   28800   35000   42000   50500   60500   73000   90000  114000  130000
DQ150000  180000  230000  323000  490000  640000  840000 1000000
DC1          100     170     220     300     400     520     750    1100    1450
DC   1900    2800    4900    9800   12200   13320   14170   14660
ZR A=FORD B=SITE04 C=FREQ-FLOW F=BASE
ZR A=FORD B=SITE04 C=FLOW-DAMAGE F=BASE
ED
BF      0      18       0       057060610       0       6
FC     .3       1     1.5       2       3       4
ZWQF   A=FORD C=FREQ-FLOW
ZW  A=FORD B=ALL CATE C=REACH-EAD
IN      1  6 JUNE    1000    2000    3000   18000   37000   42000   50000   27000
IN 20000   13000    5000    4000    3000    2000    1000    1000    1000    1000
IN      2  6 JUNE    2000    3000    4000    6000   20000   57000  100000   90000
IN 70000   50000   37000   24000   24000   15000    9000    3000    2000    1500
IN      3  6 JUNE    3000    6000   27000   60000  105000   78000   60000   45000
IN 33000   24000   18000   12000   12000    9000    6000    3000    2000    1000
IN      4  6 JUNE    2000    4000   19000   13000   10000    7000    4000    1000
IN  1000    4000   10000   25000   13000    7000    4000    2000    1000     500
EJ
ER
```

Appendix D

Branch-and-Bound Program Output

The branch-and-bound program output for the Fall River example is shown on the following pages. The following discussion explains the output with key items numbered for reference. The input consists of all proposed measures in an HEC-5 format as described in Appendix C, with the new BB and EB records used to separate the discrete alternatives.

The J4 record **1** (field 10=2) is required to write the flow-frequency curves to the DSS file at all damage locations. The existing condition for site 1 begins with a BB record **2** , signifying site 1 (field 1=1), and measure 1 (field 2=1). Field 10 of the first BB record controls the type of output (1 = summary output, 2 = summary and intermediate output). The HEC-5 input requires that the most upstream site on every branch be a reservoir. Existing conditions were modeled by placing a "dummy" reservoir at these points. A "dummy" reservoir is a reservoir which is given a very small storage volume and for which outflow is set equal to inflow. This effectively allows no water to be stored and the site becomes an uncontrolled point on the stream. The storages are shown on the RL record **3** and the unlimited outlet capacity on the RQ record. **4** The ID record **5** contains a four character site identifier in fields 2 through 5 and a two-digit number corresponding to the site number (SITE01). The RT record **6** shows that the flows are routed from site 1 to site 2. The EB record **7** signifies the end of the data for this measure.

An M$ record **8** is used to represent the total annualized cost to implement the measure. ZR records **9** are required within the BB-EB block of data for each measure (except for existing condition). The function (or functions) this measure modifies is given by the C-part. The A-part is the project name, the B-part the downstream site which will be affected by this measure, and the F-part the four-character string "PLAN". The measure at site 1 will alter the flow-frequency function at damage locations downstream of sites 1 and 4. Two ZR records are therefore required. The B-part must be the exact six-character identifier found on the ID-record in order for the correct DSS data to be used by EAD.

Damage records DA, DF, DQ, and DC **10** are required to describe base conditions for each damage site. Percent exceedence frequency, flow, and corresponding damages are on the DF, DQ, and DC records respectively. ZR records corresponding to this base condition data follow **11** . Again, the B-part must exactly match the first field of the ID record and the F-part must be the four-character string "BASE".

Data describing site 2 is entered in similar fashion, with the proposed reservoir modifying the flow-frequency function only at site 4. There are no damages occurring directly downstream of site 2 so no damage records are required. The proposed reservoir, however, modifies the flow-frequency function at site 4. A ZR record **12** is required to supply this information.

Similarly, the proposed reservoirs at site 3 affect the flow-frequency function at site 4, shown by the ZR records **13** and **14** .

The proposed channel improvement at site 4 modifies the flow-damage function at this site. The new flow-damage function is analyzed outside of this program and entered into the DSS file prior to the branch-and-bound evaluation. A ZR record identifies this data **15** . An alternative way to describe a channel improvement is to enter stage-flow and stage-damage functions for this measure.

The F-part is "PLAN" is all cases. Thus only one alternative which modifies a function other then flow-frequency may be analyzed for each site. Note also that this example performs the expected annual damage computations using six ratios of the input hydrograph (FC record) **16** .

The branch-and-bound output begins with a summary of the system analyzed **17** , including number of sites in the system and number of measures proposed at each site. Sixteen plans are enumerated in this example **18** . An economic summary of the optimum plan follows **19** . Intermediate output of all plans enumerated **20** gives more detailed information about the branch-and-bound process and provides economic summaries of the intermediate plans.

Branch-and-Bound Program Output

```
    ++++++++++++++++++++++++++++++++++++++++
    + BRANCH-AND-BOUND ENUMERATION PROGRAM +
    +  VERSION DATE:      OCTOBER 31, 1986 +
    ++++++++++++++++++++++++++++++++++++++++



     ***** INPUT LISTING *****



    T1      BRANCH-AND-BOUND TEST DATA            FORD RIVER SYSTEM
    T2      BASED ON HEC-5 STANDARD TEST 10
    T3      THREE RESERVOIR SYSTEM - TWO FLOODING SITES
    J1      0       1       4       2       3       1
    J2     24       0    .167               1
    J3      6                      -1               1
1   J4      1                                                                      2
    J8   1.10    1.12    1.13    2.10    2.12    2.13    3.12    3.13    3.10    4.04
    C
    C
    C ******************************************************************************
    C                               SITE 1
    C ******************************************************************************
    C
    C SITE 1 MEASURE 1 = EXISTING CONDITIONS
    C   ____________________________________________________________________
2   BB      1       1                                                              2
3   RL      1      .1      .1      .2      .3      .4
    RO
    RS      2      .1      .4
4   RQ      2      -1      -1
    CP      1    6000
5   IDSITE01
6   RT      1       2      .1     1.0
7   EB
    C
    C___________________________________________________________________
    C
    C SITE 1 MEASURE 2 = RESERVOIR
    C____________________________________________________________________
    BB      1       2
    RL      1   50000       0   50000  150832  200000
    RO      1       2
    RS      6       0   50000   70000  100000  150832  200000
    RQ      6    5000    6500    7000    8000  100000  200000
    R2 99999   99999
    CP      1    6000
    IDSITE01
    RT      1       2      .1     1.0
8   M$  760.
9   ZR A=FORD B=SITE01 C=FREQ-FLOW F=PLAN
    ZR A=FORD B=SITE04 C=FREQ-FLOW F=PLAN
    EB
10  DA1
    DF     17    .999    .900    .800    .700    .600    .500    .400    .300    .250
    DF   .200    .150    .100    .050    .020    .010    .005    .002
    DQ     17   28800   35000   42000   50500   60500   73000   90000  114000  130000
    DQ150000  180000  230000  323000  490000  640000  840000 1000000
    DC1            50      80     100     110     140     190     290     380     480
    DC    600     800    1210    2200    4200    5380    6120    6500
11  ZR A=FORD B=SITE01 C=FREQ-FLOW F=BASE
    ZR A=FORD B=SITE01 C=FLOW-DAMAGE F=BASE
```

```
   C
   C ******************************************************************************
   C                             SITE 2
   C ******************************************************************************
   C
   C SITE 2 MEASURE 1 = EXISTING CONDITIONS
   C ___________________________________________________________________
   BB      2       1
   CP      2   21000
   IDSITE02
   RT      2       4      .1     3.1
   EB
   C
   C___________________________________________________________________
   C
   C SITE 2 MEASURE 2 = RESERVOIR
   C ____________________________________________________________________
   BB      2       2
   RL      2  100000       0  100000  654576 1000000
   RO      1       4
   RS      7       0  100000  200000  400000  600000  800000 1000000
   RQ      7   18000   21000   30000   40000  100000  300000  500000
   R2 99999   99999
   CP      2   21000
   IDSITE02
   RT      2       4      .1     3.1
   M$  400.
12 ZR A=FORD B=SITE04 C=FREQ-FLOW F=PLAN
   EB
   C
   C ******************************************************************************
   C                               SITE 3
   C ******************************************************************************
   C
   C SITE 3 MEASURE 1 = EXISTING CONDITIONS
   C ___________________________________________________________________
   BB      3       1
   RL      3      .3      .2      .3      .4      .5
   RO
   RS      2      .1      .5
   RQ      2      -1      -1
   CP      3   12000
   IDSITE03
   RT      3       4      .1     3.2
   EB
   C
   C ___________________________________________________________________
   C
   C SITE 3 MEASURE 2 = 800000 AC-FT FLOOD STORAGE
   C ___________________________________________________________________
   BB      3       2
   RL      3  200000       0  100000  900000 1000000
   RO      1       4
   RS      7       0  100000  200000  400000  600000  800000 1000000
   RQ      7   18000   21000   30000   40000  100000  300000  500000
   R2 99999   99999
   CP      3   12000
   IDSITE03
   RT      3       4      .1     3.2
   DR      3                                                   5000
   M$  800.
13 ZR A=FORD B=SITE04 C=FREQ-FLOW F=PLAN
   EB
   C
   C ___________________________________________________________________
   C
   C SITE 3 MEASURE 3 = 300000 AC-FT FLOOD STORAGE
   C ___________________________________________________________________
   BB      3       3
   RL      3  200000       0  600000  900000 1000000
   RO      1       4
   RS      7       0  100000  200000  400000  600000  800000 1000000
   RQ      7   18000   21000   30000   40000  100000  300000  500000
```

```
   R2 99999   99999
   CP     3   12000
   IDSITE03
   RT     3       4      .1     3.2
   DR     3                                                   5000
   M$  300.
14 ZR A=FORD B=SITE04 C=FREQ-FLOW F=PLAN
   EB
   C
   C ******************************************************************************
   C                                    SITE 4
   C ******************************************************************************
   C
   C SITE 4 MEASURE 1 = EXISTING CONDITIONS
   C __________________________________________________________________
   C
   BB     4       1
   CP     4   40000
   IDSITE04
   RT     4
   EB
   C __________________________________________________________________
   C
   C SITE 4 MEASURE 2 = CHANNEL IMPROVEMENT
   C __________________________________________________________________
   BB     4       2
   CP     4   40000
   IDSITE04
   RT     4
   QS     9   10000   20000   30000   40000  100000  300000  500000  700000  900000
   EL     9     300     350     450     500     550     600     625     650     700
   C$ 40000    2000    4000    5000    6000
   M$   25.
15 ZR A=FORD B=SITE04 C=FLOW-DAMAGE F=PLAN
   EB
   DA1
   DF    17    .999    .900    .800    .700    .600    .500    .400    .300    .250
   DF  .200    .150    .100    .050    .020    .010    .005    .002
   DQ    17   28800   35000   42000   50500   60500   73000   90000  114000  130000
   DQ150000  180000  230000  323000  490000  640000  840000 1000000
   DC1          100     170     220     300     400     520     750    1100    1450
   DC  1900    2800    4900    9800   12200   13320   14170   14660
   ZR A=FORD B=SITE04 C=FREQ-FLOW F=BASE
   ZR A=FORD B=SITE04 C=FLOW-DAMAGE F=BASE
   ED
   BF     0      18       0       057060610       0       6
16 FC    .3       1     1.5       2       3       4
   ZWQF   A=FORD C=FREQ-FLOW
   ZW  A=FORD B=ALL CATE C=REACH-EAD
   IN     1  6 JUNE    1000    2000    3000   18000   37000   42000   50000   27000
   IN 20000   13000    5000    4000    3000    2000    1000    1000    1000    1000
   IN     2  6 JUNE    2000    3000    4000    6000   20000   57000  100000   90000
   IN 70000   50000   37000   24000   24000   15000    9000    3000    2000    1500
   IN     3  6 JUNE    3000    6000   27000   60000  105000   78000   60000   45000
   IN 33000   24000   18000   12000   12000    9000    6000    3000    2000    1000
   IN     4  6 JUNE    2000    4000   19000   13000   10000    7000    4000    1000
   IN  1000    4000   10000   25000   13000    7000    4000    2000    1000     500
   EJ
   ER


   ***** END OF INPUT LISTING *****
```

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          *************************************
          *                                   *
17        *  BRANCH-AND-BOUND SUMMARY OUTPUT  *
          *                                   *
          *************************************


      SYSTEM SUMMARY
      ______________

      NUMBER OF SITES IN SYSTEM . . . . . . . . 4

      TOTAL NUMBER OF MEASURES PROPOSED . . . . 9

           MEASURES PROPOSED AT SITE  1 . . . . 2

           MEASURES PROPOSED AT SITE  2 . . . . 2

           MEASURES PROPOSED AT SITE  3 . . . . 3

           MEASURES PROPOSED AT SITE  4 . . . . 2

18     NUMBER OF PLANS ENUMERATED. . . . . . . .16


19     ECONOMIC SUMMARY OF OPTIMUM PLAN
      ________________________________

      THE MAXIMUM OBJECTIVE FUNCTION IS. . . . . . .     789.77

      THE OPTIMAL PLAN INCLUDES THE FOLLOWING MEASURES :

        SITE  1     MEASURE  1

        SITE  2     MEASURE  2

        SITE  3     MEASURE  3

        SITE  4     MEASURE  2

      EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
      EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .    732.24
      EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1514.77

      TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .    725.00
      EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    789.77


      **************************************************
      *                                                *
20    *  INTERMEDIATE OUTPUT OF ALL PLANS ENUMERATED   *
      *                                                *
      **************************************************


  ______________________________________________________________________
           PLAN  1
           ________

        SITE  1      MEASURE  1
        SITE  2      MEASURE  1
        SITE  3      MEASURE  1
        SITE  4      MEASURE  1

       THE OBJECTIVE FUNCTION IS . . . . . . . . . . .       0.00
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```
     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .      0.00

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .      0.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .      0.00
________________________________________________________________________


     COMPARE


................................................................................
     OBJECTIVE FUNCTION (      0.00) IS GREATER THAN TRIAL OPTIMUM (   -999.00)

     SET NEW TRIAL OPTIMUM TO       0.00
................................................................................

          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 1
           BOUND =   1687.51

     BOUND (   1687.51)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (      0.00).
     FURTHER DIVIDE SUBSET


          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 1
           SITE = 2     MEASURE = 1
           BOUND =   1687.51

     BOUND (   1687.51)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (      0.00).
     FURTHER DIVIDE SUBSET


          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 1
           SITE = 2     MEASURE = 1
           SITE = 3     MEASURE = 1
           BOUND =   1128.02

     BOUND (   1128.02)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (      0.00).
     FURTHER DIVIDE SUBSET



_____________________________________________________________________
           PLAN  2
          ________

      SITE  1      MEASURE  1
      SITE  2      MEASURE  1
      SITE  3      MEASURE  1
      SITE  4      MEASURE  2

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .      3.86


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   2218.15
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .     28.86

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .     25.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .      3.86
________________________________________________________________________
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```
     COMPARE


..............................................................................
     OBJECTIVE FUNCTION (      3.86) IS GREATER THAN TRIAL OPTIMUM (       0.00)

     SET NEW TRIAL OPTIMUM TO       3.86
..............................................................................

______________________________________________________________________
           PLAN  3
          ________

      SITE  1      MEASURE  1
      SITE  2      MEASURE  1
      SITE  3      MEASURE  2
      SITE  4      MEASURE  1

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .     70.65


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1376.36
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .    870.65

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .    800.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .     70.65
______________________________________________________________________

     COMPARE


..............................................................................
     OBJECTIVE FUNCTION (     70.65) IS GREATER THAN TRIAL OPTIMUM (       3.86)

     SET NEW TRIAL OPTIMUM TO      70.65
..............................................................................

          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 1
           SITE = 2     MEASURE = 1
           SITE = 3     MEASURE = 2
           BOUND =    887.51

     BOUND (    887.51)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (      70.65).
     FURTHER DIVIDE SUBSET



______________________________________________________________________
           PLAN  4
          ________

      SITE  1      MEASURE  1
      SITE  2      MEASURE  1
      SITE  3      MEASURE  2
      SITE  4      MEASURE  2

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    109.57


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1312.44
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .    934.57

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .    825.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    109.57
______________________________________________________________________
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```
    COMPARE


.................................................................................
    OBJECTIVE FUNCTION (     109.57) IS GREATER THAN TRIAL OPTIMUM (       70.65)

    SET NEW TRIAL OPTIMUM TO      109.57
.................................................................................


          PLAN  5


     SITE  1       MEASURE  1
     SITE  2       MEASURE  1
     SITE  3       MEASURE  3
     SITE  4       MEASURE  1

    THE OBJECTIVE FUNCTION IS . . . . . . . . . . .     584.39


    EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .    2247.01
    EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .    1362.62
    EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .     884.39

    TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .     300.00
    EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .     584.39


    COMPARE


.................................................................................
    OBJECTIVE FUNCTION (     584.39) IS GREATER THAN TRIAL OPTIMUM (      109.57)

    SET NEW TRIAL OPTIMUM TO      584.39
.................................................................................

         EVALUATE SUBSET BOUND
    SUBSET INCLUDES THE FOLLOWING SITES:

          SITE = 1      MEASURE = 1
          SITE = 2      MEASURE = 1
          SITE = 3      MEASURE = 3
          BOUND =    1387.51

    BOUND (    1387.51)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (     584.39).
    FURTHER DIVIDE SUBSET



          PLAN  6


     SITE  1       MEASURE  1
     SITE  2       MEASURE  1
     SITE  3       MEASURE  3
     SITE  4       MEASURE  2

    THE OBJECTIVE FUNCTION IS . . . . . . . . . . .     624.45


    EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .    2247.01
    EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .    1297.56
    EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .     949.45

    TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .     325.00
    EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .     624.45
```

```
    COMPARE


.......................................................................
    OBJECTIVE FUNCTION (    624.45) IS GREATER THAN TRIAL OPTIMUM (    584.39)

    SET NEW TRIAL OPTIMUM TO     624.45
.......................................................................

    BOUND (    624.45)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (    624.45).
    FURTHER DIVIDE SUBSET



_______________________________________________________________
          PLAN  7
         ________

     SITE  1       MEASURE  1
     SITE  2       MEASURE  2
     SITE  3       MEASURE  1
     SITE  4       MEASURE  1

    THE OBJECTIVE FUNCTION IS . . . . . . . . . . .     709.86


    EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .    2247.01
    EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .    1137.15
    EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .    1109.86

    TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .     400.00
    EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .     709.86
_______________________________________________________________

    COMPARE


.......................................................................
    OBJECTIVE FUNCTION (    709.86) IS GREATER THAN TRIAL OPTIMUM (    624.45)

    SET NEW TRIAL OPTIMUM TO     709.86
.......................................................................

         EVALUATE SUBSET BOUND
    SUBSET INCLUDES THE FOLLOWING SITES:

          SITE = 1     MEASURE = 1
          SITE = 2     MEASURE = 2
          BOUND =    1287.51

    BOUND (   1287.51)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (    709.86).
    FURTHER DIVIDE SUBSET


         EVALUATE SUBSET BOUND
    SUBSET INCLUDES THE FOLLOWING SITES:

          SITE = 1     MEASURE = 1
          SITE = 2     MEASURE = 2
          SITE = 3     MEASURE = 1
          BOUND =     328.02

BOUND IS LESS THAN TRIAL OPTIMUM. ELIMINATE SUBSET

_______________________________________________________________
          PLAN  8
         ________

     SITE  1       MEASURE  1
     SITE  2       MEASURE  2
     SITE  3       MEASURE  2
     SITE  4       MEASURE  1
```

```
     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    115.17


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .    931.84
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1315.17

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .   1200.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    115.17
________________________________________________________________________


     COMPARE


..............................................................................
     OBJECTIVE FUNCTION (    115.17) IS LESS THAN TRIAL OPTIMUM (    709.86)

     DO NOT UPDATE TRIAL OPTIMUM

________________________________________________________________________
           PLAN  9
          ________

      SITE  1       MEASURE  1
      SITE  2       MEASURE  2
      SITE  3       MEASURE  2
      SITE  4       MEASURE  2

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    286.84


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .    735.17
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1511.84

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .   1225.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    286.84
________________________________________________________________________


     COMPARE


..............................................................................
     OBJECTIVE FUNCTION (    286.84) IS LESS THAN TRIAL OPTIMUM (    709.86)

     DO NOT UPDATE TRIAL OPTIMUM

________________________________________________________________________
           PLAN 10
          ________

      SITE  1       MEASURE  1
      SITE  2       MEASURE  2
      SITE  3       MEASURE  3
      SITE  4       MEASURE  1

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    682.06


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .    864.95
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1382.06

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .    700.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    682.06
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```
 COMPARE


..........................................................................
 OBJECTIVE FUNCTION (    682.06) IS LESS THAN TRIAL OPTIMUM (     709.86)

 DO NOT UPDATE TRIAL OPTIMUM
      EVALUATE SUBSET BOUND
 SUBSET INCLUDES THE FOLLOWING SITES:

       SITE = 1     MEASURE = 1
       SITE = 2     MEASURE = 2
       SITE = 3     MEASURE = 3
       BOUND =    987.51

 BOUND (    987.51)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (     709.86).
 FURTHER DIVIDE SUBSET



 ______________________________________________________________________
           PLAN 11
          ________

  SITE  1       MEASURE  1
  SITE  2       MEASURE  2
  SITE  3       MEASURE  3
  SITE  4       MEASURE  2

 THE OBJECTIVE FUNCTION IS . . . . . . . . . . .     789.77


 EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .    2247.01
 EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .     732.24
 EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .    1514.77

 TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .     725.00
 EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .     789.77
 ______________________________________________________________________

 COMPARE


..........................................................................
 OBJECTIVE FUNCTION (    789.77) IS GREATER THAN TRIAL OPTIMUM (     709.86)

 SET NEW TRIAL OPTIMUM TO     789.77
..........................................................................


 ______________________________________________________________________
           PLAN 12
          ________

  SITE  1       MEASURE  2
  SITE  2       MEASURE  1
  SITE  3       MEASURE  1
  SITE  4       MEASURE  1

 THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    -258.81


 EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .    2247.01
 EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .    1745.82
 EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .     501.19

 TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .     760.00
 EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    -258.81
 ______________________________________________________________________
```

```
     COMPARE


.............................................................................
     OBJECTIVE FUNCTION (    -258.81) IS LESS THAN TRIAL OPTIMUM (     789.77)

     DO NOT UPDATE TRIAL OPTIMUM
          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 2
           BOUND =   1045.05

     BOUND (   1045.05)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (     789.77).
     FURTHER DIVIDE SUBSET


          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 2
           SITE = 2     MEASURE = 1
           BOUND =   1045.05

     BOUND (   1045.05)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (     789.77).
     FURTHER DIVIDE SUBSET


          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 2
           SITE = 2     MEASURE = 1
           SITE = 3     MEASURE = 1
           BOUND =   -156.91

BOUND IS LESS THAN TRIAL OPTIMUM. ELIMINATE SUBSET


           PLAN 13


      SITE  1      MEASURE  2
      SITE  2      MEASURE  1
      SITE  3      MEASURE  2
      SITE  4      MEASURE  1

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .   -408.32


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1095.33
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1151.68

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .   1560.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .   -408.32


     COMPARE


.............................................................................
     OBJECTIVE FUNCTION (    -408.32) IS LESS THAN TRIAL OPTIMUM (     789.77)

     DO NOT UPDATE TRIAL OPTIMUM
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          PLAN 14
         ________

      SITE  1      MEASURE  2
      SITE  2      MEASURE  1
      SITE  3      MEASURE  2
      SITE  4      MEASURE  2

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .   -341.84


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1003.85
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1243.16

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .   1585.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .   -341.84
 ______________________________________________________________________


     COMPARE


.............................................................................
     OBJECTIVE FUNCTION (   -341.84) IS LESS THAN TRIAL OPTIMUM (    789.77)

     DO NOT UPDATE TRIAL OPTIMUM

 ______________________________________________________________________
          PLAN 15
         ________

      SITE  1      MEASURE  2
      SITE  2      MEASURE  1
      SITE  3      MEASURE  3
      SITE  4      MEASURE  1

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    137.57


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1049.44
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1197.57

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .   1060.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    137.57
 ______________________________________________________________________


     COMPARE


.............................................................................
     OBJECTIVE FUNCTION (    137.57) IS LESS THAN TRIAL OPTIMUM (    789.77)

     DO NOT UPDATE TRIAL OPTIMUM
          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 2
           SITE = 2     MEASURE = 1
           SITE = 3     MEASURE = 3
           BOUND =    745.05

BOUND IS LESS THAN TRIAL OPTIMUM. ELIMINATE SUBSET

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        PLAN 16
       ---------
     SITE  1      MEASURE  2
     SITE  2      MEASURE  2
     SITE  3      MEASURE  1
     SITE  4      MEASURE  1

    THE OBJECTIVE FUNCTION IS . . . . . . . . . . .     85.05


    EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
    EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1001.96
    EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1245.05

    TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .   1160.00
    EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .     85.05
-----------------------------------------------------------------------


    COMPARE


...............................................................................
    OBJECTIVE FUNCTION (      85.05) IS LESS THAN TRIAL OPTIMUM (      789.77)

    DO NOT UPDATE TRIAL OPTIMUM
         EVALUATE SUBSET BOUND
    SUBSET INCLUDES THE FOLLOWING SITES:

          SITE = 1      MEASURE = 2
          SITE = 2      MEASURE = 2
          BOUND =     641.83

BOUND IS LESS THAN TRIAL OPTIMUM. ELIMINATE SUBSET
    ***** END OF BRANCH-AND-BOUND OUTPUT *****
```

Appendix E

Sensitivity Analysis Output

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+++++++++++++++++++++++++++++++++++++++++
+  BRANCH-AND-BOUND ENUMERATION PROGRAM +
+  VERSION DATE:      OCTOBER 31, 1986  +
+++++++++++++++++++++++++++++++++++++++++



***** INPUT LISTING *****



T1      BRANCH-AND-BOUND TEST DATA            FALL RIVER SYSTEM
T2      SENSITIVITY ANALYSIS
T3      THREE RESERVOIR SYSTEM - TWO FLOODING SITES
J1     0       1       4       2       3       1
J2    24       0    .167               1
J3     6                      -1               1
J4     1                                                                       2
J8  1.10    1.12    1.13    2.10    2.12    2.13    3.12    3.13    3.10    4.04
C
C
C ******************************************************************************
C                               SITE 1
C ******************************************************************************
C
C SITE 1 MEASURE 1 = EXISTING CONDITIONS
C ____________________________________________________________________
BB     1       1                                                       2
RL     1      .1      .1      .2      .3      .4
RO
RS     2      .1      .4
RQ     2      -1      -1
CP     1    6000
IDSITE01
RT     1       2      .1     1.0
EB
C
C ______________________________________________________________________
C
C SITE 1 MEASURE 2 = RESERVOIR
C ______________________________________________________________________
BB     1       2
RL     1   50000       0   50000  150832  200000
RO     1       2
RS     6       0   50000   70000  100000  150832  200000
RQ     6    5000    6500    7000    8000  100000  200000
R2 99999   99999
CP     1    6000
IDSITE01
RT     1       2      .1     1.0
M$  760.
ZR A=FORD B=SITE01 C=FREQ-FLOW F=PLAN
ZR A=FORD B=SITE04 C=FREQ-FLOW F=PLAN
EB
DA1
DF    17    .999    .900    .800    .700    .600    .500    .400    .300    .250
DF  .200    .150    .100    .050    .020    .010    .005    .002
DQ    17   28800   35000   42000   50500   60500   73000   90000  114000  130000
DQ150000  180000  230000  323000  490000  640000  840000 1000000
DC1             50      80     100     110     140     190     290     380     480
DC   600     800    1210    2200    4200    5380    6120    6500
```

```
ZR A=FORD B=SITE01 C=FREQ-FLOW F=BASE
ZR A=FORD B=SITE01 C=FLOW-DAMAGE F=BASE
C
C ********************************************************************************
C                                       SITE 2
C ********************************************************************************
C
C SITE 2 MEASURE 1 = EXISTING CONDITIONS
C ____________________________________________________________________
BB      2       1
CP      2   21000
IDSITE02
RT      2       4      .1     3.1
EB
C
C ____________________________________________________________________
C
C SITE 2 MEASURE 2 = RESERVOIR
C ____________________________________________________________________
BB      2       2
RL      2  100000       0  100000  654576 1000000
RO      1       4
RS      7       0  100000  200000  400000  600000  800000 1000000
RQ      7   18000   21000   30000   40000  100000  300000  500000
R2 99999   99999
CP      2   21000
IDSITE02
RT      2       4      .1     3.1
M$  400.
ZR A=FORD B=SITE04 C=FREQ-FLOW F=PLAN
EB
C
C ********************************************************************************
C                                         SITE 3
C ********************************************************************************
C
C SITE 3 MEASURE 1 = EXISTING CONDITIONS
C ____________________________________________________________________
BB      3       1
RL      3      .3      .2      .3      .4      .5
RO
RS      2      .1      .5
RQ      2      -1      -1
CP      3   12000
IDSITE03
RT      3       4      .1     3.2
EB
C
C ____________________________________________________________________
C
C SITE 3 MEASURE 2 = 300000 AC-FT FLOOD STORAGE
C ____________________________________________________________________
BB      3       2
RL      3  200000       0  600000  900000 1000000
RO      1       4
RS      7       0  100000  200000  400000  600000  800000 1000000
RQ      7   18000   21000   30000   40000  100000  300000  500000
R2 99999   99999
CP      3   12000
IDSITE03
RT      3       4      .1     3.2
DR      3                                                   5000
M$  300.
ZR A=FORD B=SITE04 C=FREQ-FLOW F=PLAN
EB
C ____________________________________________________________________
C
C SITE 3 MEASURE 3 = 800000 AC-FT FLOOD STORAGE
C ____________________________________________________________________
BB      3       3
RL      3  200000       0  100000  900000 1000000
RO      1       4
RS      7       0  100000  200000  400000  600000  800000 1000000
```

```
 RQ     7   18000   21000   30000   40000  100000  300000  500000
 R2 99999   99999
 CP     3   12000
 IDSITE03
 RT     3       4      .1     3.2
 DR     3                                                    5000
 M$  800.
 ZR A=FORD B=SITE04 C=FREQ-FLOW F=PLAN
 EB
 C
 C
 C ******************************************************************************
 C                                    SITE 4
 C ******************************************************************************
 C
 C SITE 4 MEASURE 1 = EXISTING CONDITIONS
 C _____________________________________________________________________
 C
 BB     4       1
 CP     4   40000
 IDSITE04
 RT     4
 EB
 C _____________________________________________________________________
 C
 C SITE 4 MEASURE 2 = CHANNEL IMPROVEMENT
 C _____________________________________________________________________
 BB     4       2
 CP     4   40000
 IDSITE04
 RT     4
 QS     9   10000   20000   30000   40000  100000  300000  500000  700000  900000
 EL     9     300     350     450     500     550     600     625     650     700
 C$ 40000    2000    4000    5000    6000
 M$   25.
 ZR A=FORD B=SITE04 C=FLOW-DAMAGE F=PLAN
 EB
 DA1
 DF    17    .999    .900    .800    .700    .600    .500    .400    .300    .250
 DF  .200    .150    .100    .050    .020    .010    .005    .002
 DQ    17   28800   35000   42000   50500   60500   73000   90000  114000  130000
 DQ150000  180000  230000  323000  490000  640000  840000 1000000
 DC1          100     170     220     300     400     520     750    1100    1450
 DC  1900    2800    4900    9800   12200   13320   14170   14660
 ZR A=FORD B=SITE04 C=FREQ-FLOW F=BASE
 ZR A=FORD B=SITE04 C=FLOW-DAMAGE F=BASE
 ED
 BF     0      18       0       057060610       0       6
 FC    .3       1     1.5       2       3       4
 ZWQF   A=FORD C=FREQ-FLOW
 ZW  A=FORD B=ALL CATE C=REACH-EAD
 IN     1  6 JUNE    1000    2000    3000   18000   37000   42000   50000   27000
 IN 20000   13000    5000    4000    3000    2000    1000    1000    1000    1000
 IN     2  6 JUNE    2000    3000    4000    6000   20000   57000  100000   90000
 IN 70000   50000   37000   24000   24000   15000    9000    3000    2000    1500
 IN     3  6 JUNE    3000    6000   27000   60000  105000   78000   60000   45000
 IN 33000   24000   18000   12000   12000    9000    6000    3000    2000    1000
 IN     4  6 JUNE    2000    4000   19000   13000   10000    7000    4000    1000
 IN  1000    4000   10000   25000   13000    7000    4000    2000    1000     500
 EJ
 ER


***** END OF INPUT LISTING *****
```

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          *************************************
          *                                   *
          *  BRANCH-AND-BOUND SUMMARY OUTPUT  *
          *                                   *
          *************************************


SYSTEM SUMMARY
______________

NUMBER OF SITES IN SYSTEM . . . . . . . . 4

TOTAL NUMBER OF MEASURES PROPOSED . . . . 9


     MEASURES PROPOSED AT SITE  1 . . . . 2

     MEASURES PROPOSED AT SITE  2 . . . . 2

     MEASURES PROPOSED AT SITE  3 . . . . 3

     MEASURES PROPOSED AT SITE  4 . . . . 2

NUMBER OF PLANS ENUMERATED. . . . . . . .15


ECONOMIC SUMMARY OF OPTIMUM PLAN
________________________________

THE MAXIMUM OBJECTIVE FUNCTION IS. . . . . . .     789.77

THE OPTIMAL PLAN INCLUDES THE FOLLOWING MEASURES :

  SITE  1     MEASURE  1

  SITE  2     MEASURE  2

  SITE  3     MEASURE  2

  SITE  4     MEASURE  2

EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .    732.24
EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1514.77

TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .    725.00
EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    789.77

 **************************************************
 *                                                *
 *  INTERMEDIATE OUTPUT OF ALL PLANS ENUMERATED   *
 *                                                *
 **************************************************


_______________________________________________________________________
       PLAN  1
      _________

  SITE  1     MEASURE  1
  SITE  2     MEASURE  1
  SITE  3     MEASURE  1
  SITE  4     MEASURE  1

 THE OBJECTIVE FUNCTION IS . . . . . . . . . . .      0.00
```

```
     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .      0.00

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .      0.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .      0.00


     COMPARE


..............................................................................
     OBJECTIVE FUNCTION (      0.00) IS GREATER THAN TRIAL OPTIMUM (   -999.00)

     SET NEW TRIAL OPTIMUM TO       0.00
..............................................................................

          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 1
           BOUND =    1687.51

     BOUND (    1687.51)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (      0.00).
     FURTHER DIVIDE SUBSET


          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 1
           SITE = 2     MEASURE = 1
           BOUND =    1687.51

     BOUND (    1687.51)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (      0.00).
     FURTHER DIVIDE SUBSET


          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 1
           SITE = 2     MEASURE = 1
           SITE = 3     MEASURE = 1
           BOUND =    1128.02

     BOUND (    1128.02)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (      0.00).
     FURTHER DIVIDE SUBSET



           PLAN  2


      SITE  1      MEASURE  1
      SITE  2      MEASURE  1
      SITE  3      MEASURE  1
      SITE  4      MEASURE  2

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .      3.86


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   2218.15
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .     28.86

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .     25.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .      3.86
```

```
     COMPARE


................................................................................
     OBJECTIVE FUNCTION (      3.86) IS GREATER THAN TRIAL OPTIMUM (       0.00)

     SET NEW TRIAL OPTIMUM TO       3.86
................................................................................


________________________________________________________________________
           PLAN  3
          ________

      SITE  1      MEASURE  1
      SITE  2      MEASURE  1
      SITE  3      MEASURE  2
      SITE  4      MEASURE  1

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    584.39


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1362.62
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .    884.39

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .    300.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    584.39
________________________________________________________________________


     COMPARE


................................................................................
     OBJECTIVE FUNCTION (    584.39) IS GREATER THAN TRIAL OPTIMUM (       3.86)

     SET NEW TRIAL OPTIMUM TO     584.39
................................................................................

          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 1
           SITE = 2     MEASURE = 1
           SITE = 3     MEASURE = 2
           BOUND =   1387.51

     BOUND (   1387.51)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (    584.39).
     FURTHER DIVIDE SUBSET



________________________________________________________________________
           PLAN  4
          ________

      SITE  1      MEASURE  1
      SITE  2      MEASURE  1
      SITE  3      MEASURE  2
      SITE  4      MEASURE  2

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    624.45


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1297.56
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .    949.45

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .    325.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    624.45
________________________________________________________________________
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```
    COMPARE


..............................................................................
    OBJECTIVE FUNCTION (    624.45) IS GREATER THAN TRIAL OPTIMUM (    584.39)

    SET NEW TRIAL OPTIMUM TO     624.45
..............................................................................

    BOUND (    624.45)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (    624.45).
    FURTHER DIVIDE SUBSET


______________________________________________________________________
          PLAN  5
         ________

     SITE  1      MEASURE  1
     SITE  2      MEASURE  1
     SITE  3      MEASURE  3
     SITE  4      MEASURE  1

    THE OBJECTIVE FUNCTION IS . . . . . . . . . . .     70.65


    EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
    EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1376.36
    EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .    870.65

    TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .    800.00
    EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .     70.65
______________________________________________________________________

    COMPARE


..............................................................................
    OBJECTIVE FUNCTION (     70.65) IS LESS THAN TRIAL OPTIMUM (    624.45)

    DO NOT UPDATE TRIAL OPTIMUM
         EVALUATE SUBSET BOUND
    SUBSET INCLUDES THE FOLLOWING SITES:

          SITE = 1     MEASURE = 1
          SITE = 2     MEASURE = 1
          SITE = 3     MEASURE = 3
          BOUND =    887.51

    BOUND (    887.51)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (    624.45).
    FURTHER DIVIDE SUBSET


______________________________________________________________________
          PLAN  6
         ________

     SITE  1      MEASURE  1
     SITE  2      MEASURE  1
     SITE  3      MEASURE  3
     SITE  4      MEASURE  2

    THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    109.57


    EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
    EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1312.44
    EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .    934.57
```

```
     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .    825.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    109.57


     COMPARE

...............................................................................
     OBJECTIVE FUNCTION (    109.57) IS LESS THAN TRIAL OPTIMUM (    624.45)

     DO NOT UPDATE TRIAL OPTIMUM

           PLAN  7


      SITE  1      MEASURE  1
      SITE  2      MEASURE  2
      SITE  3      MEASURE  1
      SITE  4      MEASURE  1

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    709.86


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1137.15
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1109.86

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .    400.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    709.86


     COMPARE

...............................................................................
     OBJECTIVE FUNCTION (    709.86) IS GREATER THAN TRIAL OPTIMUM (    624.45)

     SET NEW TRIAL OPTIMUM TO     709.86
...............................................................................

          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 1
           SITE = 2     MEASURE = 2
           BOUND =   1287.51

     BOUND (   1287.51)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (    709.86).
     FURTHER DIVIDE SUBSET


          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 1
           SITE = 2     MEASURE = 2
           SITE = 3     MEASURE = 1
           BOUND =    328.02

BOUND IS LESS THAN TRIAL OPTIMUM. ELIMINATE SUBSET

           PLAN  8


      SITE  1      MEASURE  1
      SITE  2      MEASURE  2
      SITE  3      MEASURE  2
      SITE  4      MEASURE  1
```

```
     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    682.06


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .    864.95
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1382.06

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .    700.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    682.06
______________________________________________________________________


     COMPARE


................................................................................
     OBJECTIVE FUNCTION (    682.06) IS LESS THAN TRIAL OPTIMUM (    709.86)

     DO NOT UPDATE TRIAL OPTIMUM

______________________________________________________________________
           PLAN  9
          ________

      SITE  1      MEASURE  1
      SITE  2      MEASURE  2
      SITE  3      MEASURE  2
      SITE  4      MEASURE  2

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    789.77


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .    732.24
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1514.77

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .    725.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    789.77
______________________________________________________________________


     COMPARE


................................................................................
     OBJECTIVE FUNCTION (    789.77) IS GREATER THAN TRIAL OPTIMUM (    709.86)

     SET NEW TRIAL OPTIMUM TO     789.77
................................................................................


______________________________________________________________________
           PLAN 10
          ________

      SITE  1      MEASURE  1
      SITE  2      MEASURE  2
      SITE  3      MEASURE  3
      SITE  4      MEASURE  1

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    115.17


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .    931.84
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1315.17

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .   1200.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    115.17
______________________________________________________________________
```

```
     COMPARE


.............................................................................
     OBJECTIVE FUNCTION (     115.17) IS LESS THAN TRIAL OPTIMUM (     789.77)

     DO NOT UPDATE TRIAL OPTIMUM
          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 1
           SITE = 2     MEASURE = 2
           SITE = 3     MEASURE = 3
           BOUND =    487.51

BOUND IS LESS THAN TRIAL OPTIMUM. ELIMINATE SUBSET

______________________________________________________________________
           PLAN 11
          ________

      SITE  1      MEASURE  2
      SITE  2      MEASURE  1
      SITE  3      MEASURE  1
      SITE  4      MEASURE  1

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .   -258.81


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1745.82
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .    501.19

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .    760.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .   -258.81
______________________________________________________________________

     COMPARE


.............................................................................
     OBJECTIVE FUNCTION (    -258.81) IS LESS THAN TRIAL OPTIMUM (     789.77)

     DO NOT UPDATE TRIAL OPTIMUM
          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 2
           BOUND =    1045.05

     BOUND (    1045.05)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (     789.77).
     FURTHER DIVIDE SUBSET


          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 2
           SITE = 2     MEASURE = 1
           BOUND =    1045.05

     BOUND (    1045.05)IS GREATER THAN TRIAL OBJECTIVE FUNCTION (     789.77).
     FURTHER DIVIDE SUBSET
```

```
          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 2
           SITE = 2     MEASURE = 1
           SITE = 3     MEASURE = 1
           BOUND =    -156.91

BOUND IS LESS THAN TRIAL OPTIMUM. ELIMINATE SUBSET

______________________________________________________________________
           PLAN 12
          ________

      SITE  1     MEASURE  2
      SITE  2     MEASURE  1
      SITE  3     MEASURE  2
      SITE  4     MEASURE  1

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    137.57


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1049.44
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1197.57

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .   1060.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    137.57
______________________________________________________________________


     COMPARE


...............................................................................
     OBJECTIVE FUNCTION (     137.57) IS LESS THAN TRIAL OPTIMUM (     789.77)

     DO NOT UPDATE TRIAL OPTIMUM

______________________________________________________________________
           PLAN 13
          ________

      SITE  1     MEASURE  2
      SITE  2     MEASURE  1
      SITE  3     MEASURE  2
      SITE  4     MEASURE  2

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .    198.52


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .    963.49
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1283.52

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .   1085.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .    198.52
______________________________________________________________________


     COMPARE


...............................................................................
     OBJECTIVE FUNCTION (     198.52) IS LESS THAN TRIAL OPTIMUM (     789.77)

     DO NOT UPDATE TRIAL OPTIMUM


______________________________________________________________________
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          PLAN 14
         --------

      SITE  1      MEASURE  2
      SITE  2      MEASURE  1
      SITE  3      MEASURE  3
      SITE  4      MEASURE  1

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .   -408.32


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1095.33
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1151.68

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .   1560.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .   -408.32
________________________________________________________________________

     COMPARE


..........................................................................
     OBJECTIVE FUNCTION (   -408.32) IS LESS THAN TRIAL OPTIMUM (    789.77)

     DO NOT UPDATE TRIAL OPTIMUM
          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 2
           SITE = 2     MEASURE = 1
           SITE = 3     MEASURE = 3
           BOUND =    245.05

BOUND IS LESS THAN TRIAL OPTIMUM. ELIMINATE SUBSET

________________________________________________________________________
          PLAN 15
         --------

      SITE  1      MEASURE  2
      SITE  2      MEASURE  2
      SITE  3      MEASURE  1
      SITE  4      MEASURE  1

     THE OBJECTIVE FUNCTION IS . . . . . . . . . . .     85.05


     EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .   2247.01
     EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .   1001.96
     EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .   1245.05

     TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .   1160.00
     EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .     85.05
________________________________________________________________________

     COMPARE

..........................................................................
     OBJECTIVE FUNCTION (     85.05) IS LESS THAN TRIAL OPTIMUM (    789.77)

     DO NOT UPDATE TRIAL OPTIMUM
          EVALUATE SUBSET BOUND
     SUBSET INCLUDES THE FOLLOWING SITES:

           SITE = 1     MEASURE = 2
           SITE = 2     MEASURE = 2
           BOUND =    641.83

BOUND IS LESS THAN TRIAL OPTIMUM. ELIMINATE SUBSET
    ***** END OF BRANCH-AND-BOUND OUTPUT *****
```

Appendix F

Branch-and-Bound Program Listing

```
      PROGRAM BRANCH
C
C
C ***********************************************************************
C *
C *  PROGRAM BRANCH-AND-BOUND
C *
C ***********************************************************************
C
C
C      AUTHOR : TERESA H. BOWEN
C
C
C      DESCRIPTION OF SUBROUTINES
C
C ***********************************************************************
C * SUBROUTINE       * DESCRIPTION
C ***********************************************************************
C * BANNER           * WRITES OUT BANNER PAGE
C * BBOUT            * WRITES SUMMARY OUTPUT TABLE
C * EADIN1           * CREATES A BASE EAD INPUT FILE FROM USER INPUT
C * EADIN2           * CREATES AN EAD INPUT FILE WITH BASE CONDITION
C *                                 * AND PLAN1
C * HEC5IN           * CREATES AN HEC-5 INPUT FILE FROM USER INPUT
C * NETBEN           * PERFORMS FINAL ECONOMIC ANALYSIS
C * PRE              * PREPROCESSOR WHICH DEFINES AND NUMBERS AND
C *                                 * MEASURES FROM USER INPUT
C ***********************************************************************
C
C   DEFINITION OF VARIABLES USED IN THIS PROGRAM
C ***********************************************************************
C * VARIABLE       * DEFIINITON
C ***********************************************************************
C * BASEZ          * ZW RECORD WITH PARTS CORRESONDING TO BASE
C *                                 * CONDITION DAMAGES
C * BOUND          * SUBSET BOUND (DBASE - DAMAGE(KSITE)-COST(KSITE))
C * COST           * COST ARRAY OF MEASURES IN PLAN
C * CPLAN           * COST OF ALL MEASURES IN PLAN
C * DAMAGE         * DAMAGES ARRAY OF DAMAGES BY SITE IN PLAN
C * DBASE          * BASE CONDITION DAMAGES FOR ALL REACHES
C * DPLAN          * TOTAL DAMAGES WITH PLAN IMPLEMENTED
C * IMEAS          * INDEX OF MEASURES AT SITES
C * ISITE          * INDEX OF SITES
C * KSITE          * INDICATOR OF WHICH SITES ARE IN CURRENT SUBSET
C * NMEAS          * NUMBER OF MEASURES PROPOSED AT EACH SITE
C * NPLAN           * NUMBER OF PLANS ENUMERATED
C * NSITE          * NUMBER OF SITES IN SYSTEM
C * OBJFUN         * VALUE OF OBJECTIVE FUNCTION
C * PLANZ          * ZW RECORD WITH PARTS CORRESPONDING TO DAMAGES             C** WITH PLAN1
C * REDUCE         * DAMAGE REDUCTION WITH PLAN IMPLEMENTED
C * SAVDAM         * TOTAL DAMAGES FOR BEST PLAN SO FAR
C * SAVOPT         * OBJECTIVE FUNCTION FOR BEST PLAN SO FAR
C * SVCOST         * TOTAL COSTS FOR BEST PLAN SO FAR
C * SUMC           * SUM OF COSTS IN SUBSET
C * SUMD           * SUM OF DAMAGES IN SUBSET
C * TRIOPT         * VALUE OF TRIAL OPTIMUM
C ***********************************************************************
C
C
C
C
```

```
C  DIMENSIONS FOR MAXIMUM LIMITS OF ARRAYS
C
C  ************************************************************************
C  * ARRAY            *  DIMENSION              * DIMENSIONED TO
C  ************************************************************************
C  * KMEAS            *  NUMBER OF SITES        *  MSITE
C  * IMEAS            *  NUMBER OF SITES        *  MSITE
C  * DAMAGE           *  NUMBER OF SITES        *  MSITE
C  * COST             *  NUMBER OF SITES        *  MSITE
C  * ISAVE            *  NUMBER OF SITES        *  MSITE
C  ************************************************************************
C  * IBR(NUMBER OF RECORDS PER MEASURE, NUMBER OF SITES, NUMBER OF        C*MEASURE)
C  ************************************************************************
C
C
C     DESCRIPTION OF UNIT NUMBERS
C
C     ************************************************************************
C    * UNIT *  FILE    * SUBROUTINE WHICH                                * SUMMARY OF USE
C    *  NO. *  NAME    *  CREATES FILE    *
C    ************************************************************************
C    *    6 *  STDOUT  *    -              * STANDARD OUTPUT
C    *   18 *  IT2     *    -              * INTERMEDIATE RESULTS FROM
C    *      *          *                   * HEC5A
C    *   71 *  DSSFILE *    -              * STORES DSS PAIRED DATA
C    *  110 *    -     *  NONE             * USER INPUT
C    *  111 *  DATA1   *  PRE              * MASTER INPUT OF ALL ALTS.
C    *  112 *  DATA2   *  MAIN             * HEC-5/EAD INPUT OF CURRENT
C    *      *          *                   * PLAN
C    *  113 *  EADBASE *  EADIN1           * EAD INPUT FOR BASE CONDITION
C    *  114 *  EADPLAN *  EADIN2           * EAD INPUT FOR CURRENT PLAN
C    *  115 *  HEC5DATA                    *  HEC5IN                     * HEC-5 INPUT FOR CURRENT
PLAN
C    *  120 *  SUMMARY *  BBOUT            * SUMMARY OUTPUT
C    *  121 *  INTER   *  BRANCH           * INTERMEDIATE OUTPUT
C    *  122 *  EADINT   *  BRANCH          * EAD OUTPUT
C    *  123 *  H5INT   *  BRANCH           * HEC5 OUTPUT
C    ************************************************************************
C
C
C
C
C
C
C ---------------------------------------------------------------------------
       PARAMETER (MREC=30, MSITE=11, MMEAS=5, MWBUFF=82, MWDATA=300,
      .MARYLB=130, MFLTAB=1200, MPLAN=2, MSTATS=8, MHEAD=30)
C
       DIMENSION IMEAS(MSITE), KMEAS(MSITE), DAMAGE(MSITE),
      .COST(MSITE), ISAVE(MSITE), IFLTAB(MFLTAB), NSTATS(MSTATS),
      .IHEAD(MHEAD), CRCHNM(MSITE), DUMMY(MSITE,MPLAN),
      .DATA(MWDATA), IBUFF(MWBUFF), CARYLB(MARYLB),
      .DAMBAS(MSITE), ISUB(MSITE)
C
       COMMON/BR/IBR
       COMMON/COUNT/ICNT
       COMMON/SITE/NSITE,NMEAS,NPLAN
       COMMON/Z/BASEZ,PLANZ
       COMMON/ECON/COST,DAMAGE,TSNB,DBASE,SUMC,SUMD,CPLAN,DPLAN
       COMMON/OPT/ISAVE,IMEAS,KMEAS
       COMMON/KEEP/SAVOPT,SVCOST,SAVDAM
       CHARACTER IFM*10, ITO*30
       CHARACTER DSSFIL*17, H5INT*17, EADINT*17, HEC5IN*17
       CHARACTER*4 AC
       CHARACTER*32 A,B,C,D,E,F
       CHARACTER*80 CARD,ZRCARD,CPATH,BASEZ,PLANZ
       CHARACTER*80 IBR(MHEAD,MSITE,MMEAS)
       CHARACTER CFILE*20, CRCHNM*6, CFNAME*64, CDSSFN*64, C1UNIT*8,
      .C2UNIT*8, C1TYPE*4, C2TYPE*4, CARYLB*8
       CHARACTER*20 T110, T111, T112, T121, T120, T114
       LOGICAL IF
       DATA IFM/'BRANCHX'/
       DATA AC/'*ADD'/
```

```
      DATA ITO/'HEC5,INPUT=DATA2,OUTPUT=0:'/
C
C ------------------------------------------------------------------------------
      CALL ATTACH ( 6, 'OUTPUT', 'STDOUT', ' ', CFILE, ISTAT)
      CALL ATTACH ( 110, 'INPUT', 'STDIN', ' ', CFILE, ISTAT)
      T110=CFILE
      CALL ATTACH ( 71, 'DSSFILE', 'SCRATCH36','NOP', DSSFIL, ISTAT)
      CALL ATTACH ( 111, 'DATA1', 'DATA1', ' ', CFILE, ISTAT)
      T111=CFILE
      CALL ATTACH ( 112, 'DATA2', 'DATA2', ' ', CFILE, ISTAT)
      T112 = CFILE
      CALL ATTACH ( 114, 'EADPLAN', 'EADPLAN', ' ', CFILE, ISTAT)
      T114 = CFILE
      CALL ATTACH ( 120, 'SUMMARY', 'SUMMARY', ' ', CFILE, ISTAT)
      T120 = CFILE
      CALL ATTACH ( 121, 'INTER', 'INTER', ' ', CFILE, ISTAT)
      T121 = CFILE
      CALL ATTACH ( 122, 'EADINT',  'EADINT', 'NOP', EADINT, ISTAT)
      CALL ATTACH ( 123, 'H5INT', 'H5INT', 'NOP', H5INT, ISTAT)
      CALL ATTEND
C
      CALL ZSET ('UNIT', ' ', 70)
      CALL ZOPEN(IFLTAB,DSSFIL,ISTAT)
      CALL ZSET ('PROG', 'BRCH', 0)
C
C
C     CALL PREPROCESSOR WHICH READS MASTER HEC-5 INPUT FILE AND WRITES
C     AN INTERMEDIATE FILE (DATA1) CONTAINING *ADD IN PLACE OF EACH
C     BLOCK OF DATA DESCRIBING PROPOSED ALTERNATIVE
C
      CALL PRE(ISUB)
C                                                                  *************
C                                                                  * PREBRANCH *
C                                                                  *************
C
C     INITIALIZE
C                                                                 ..............
C                                                                 . INITIALIZE .
C                                                                 ..............
      TRIOPT = -999.
      ISITE = 1
      DO 90 I=1,MSITE
      IMEAS(I) = 1
      KMEAS(I) = 1
   90 CONTINUE
      NPLAN=0
      KSITE = 1
      NSITE=0
      ICNT=1
      KBOUND=-998
C
C
C
C     BASE CONDITION (STATUS QUO) IS MEASURE 1 AT EACH SITE AND IS CALLED
C     PLAN1.
C
C
  100 ISITE=1
      NPLAN=NPLAN+1
      REWIND 111
      REWIND 112
  130 READ(111,'(A80)',END=180)CARD
      IF(CARD(1:4).NE.AC) THEN
         WRITE (112,'(A80)') CARD
         GO TO 130
      ELSE
      READ(CARD(11:14),'(2I2)') JSITE, JMEAS
  150 IF(JSITE.EQ.ISITE.AND.JMEAS.EQ.IMEAS(ISITE))THEN
           DO 160 J=1,20
              IF (IBR(J,ISITE,IMEAS(ISITE)).EQ.'EB') GO TO 170
              WRITE(112,'(A80)') IBR(J,ISITE,IMEAS(ISITE))
  160      CONTINUE
  170 ISITE = ISITE + 1
```

```
      ELSE
      ENDIF
      GO TO 130
      ENDIF
  180 CONTINUE
      NSITE=ISITE-1
C
      WRITE(3,186) NPLAN
C
      DO 185 ISITE=1,NSITE
      WRITE(3,187)ISITE,IMEAS(ISITE)
  185 CONTINUE
  186 FORMAT(' THIS IS PLAN ',I2)
  187 FORMAT(' SITE = ',I2,'MEASURE = ',I2)
      WRITE(121,190) NPLAN
  190 FORMAT(/80('_')/10X,' PLAN ',I2,/10X,8('_')/)
      DO 195 ISITE=1,NSITE
      WRITE(121,198)ISITE,IMEAS(ISITE)
  195 CONTINUE
  198 FORMAT(5X,' SITE ',I2,5X' MEASURE ',I2)
      ISITE = 1
C
C
C     THE FIRST MASTER INPUT FILE GENERATED IS THE BASE CONDITION (PLAN1).
C     FOR THIS FIRST ITERATION, CALL EADIN1 WHICH CREATES A BASE CONDITION
C     EAD FILE (EADBASE) FROM THE MASTER BASE CONDITION FILE (DATA2).
C
      IF (ICNT.EQ.1) THEN
      CALL EADIN1(IHEAD, NSTATS,IFLTAB)
C                                                                 **********
C                                                                 * EADIN1 *
C                                                                 **********
      ELSE
C
C
C     CALL EADIN2 FOR ALL SUBSEQUENT PLANS.
C     THIS SUBROUTINE ADDS ZR RECORDS DESCRIBING CAHNGED FUNCTIONS IN THIS
C     PLAN TO THE BASE EADFILE.
C
      WRITE(3,*) 'PROGRAM CALL TO EADIN2'
C
      CALL EADIN2(IHEAD,NSTATS,IFLTAB)
C                                                                 **********
C                                                                 * EADIN2 *
C                                                                 **********
C
      ENDIF
C
C
      REWIND 112
C
C     IF THIS IS THE FIRST ITERATION, EXECUTE HEC-5 FOR BASE CONDITION
C     RELATIONSHIPS
C
      IF(ICNT.EQ.1)GO TO 400
C
C     IF FLOW-FREQUENCY FUNCTION IS MODIFIED AT ANY SITE IN THIS PLAN,
C     HEC-5 MUST BE EXECUTED. IF NOT, EXECUTE ONLY EAD.
C
C
C     LOOK FOR A C=FREQ-FLOW PART IN ZR RECORDS IN THE DATA2 FILE.
C
C
  250 READ(112,'(A80)',END=380) CARD
      IF(CARD(1:2).EQ.'DA')THEN
      READ(112,'(A80)',END=380) CARD
      READ(112,'(A80)',END=380) CARD
      READ(112,'(A80)',END=380) CARD
      READ(112,'(A80)',END=380) CARD
      READ(112,'(A80)',END=380) CARD
      READ(112,'(A80)',END=380) CARD
      READ(112,'(A80)',END=380) CARD
      READ(112,'(A80)',END=380) CARD
```

```
      READ(112,'(A80)',END=380) CARD
      ENDIF
      IF(CARD(1:2).EQ.'ZR')THEN
      ZRCARD=CARD
C
      DO 270 I=1,6
      NSTATS(I) = -32
  270 CONTINUE
C
      CALL ZGPNP (ZRCARD,A,B,C,D,E,F,NSTATS)
      IF (NSTATS(1).GE.0) NA = NSTATS(1)
      IF (NSTATS(2).GE.0) NB = NSTATS(2)
      IF (NSTATS(3).GE.0) NC = NSTATS(3)
      IF (NSTATS(4).GE.0) ND = NSTATS(4)
      IF (NSTATS(5).GE.0) NE = NSTATS(5)
      IF (NSTATS(6).GE.0) NF = NSTATS(6)
      CALL CHABLK (CPATH,1,80)
      CALL ZFPN(A,NA,B,NB,C,NC,D,ND,E,NE,F,NF,CPATH,NPATH)
C
C     TEST C PART OF EACH ZR RECORD
C
C     IF A FREQ-FLOW PART IS FOUND GO TO CALL HEC5IN TO CREATE AN HEC-5 FILE
C     IF NO FREQ-FLOW PART IS FOUND, READ NEXT ZR RECORD
C
  350 IF(C(1:NC).EQ.'FREQ-FLOW')GO TO 399
      GO TO 250
      ELSE
      GO TO 250
      ENDIF
  380 CONTINUE
      GO TO 450
C
C     IF A FREQ-FLOW PART WAS FOUND, RUN HEC-5
C
C     CALL HEC5IN WHICH CREATES AN HEC-5 EXECUTABLE INPUT FILE (HEC5DATA)
C     FROM THE DATA2 INPUT FILE.
C
  399 WRITE(3,*) 'CALL TO HEC5IN'
  400 CALL HEC5IN
C                                                                     **********
C                                                                     * HEC5IN *
C                                                                     **********
C
C
C                                                                 ..............
C                                                                 .  EVALUATE  .
C                                                                 . OBJECTIVE  .
C                                                                 .  FUNCTION  .
C                                                                 ..............
C
      WRITE (3,*)' CALLING H5A'
C
      CALL LASTCH ( H5INT, 17, ILAST)
      CALL EXPROG('H5A*H5A INPUT=HEC5DATA OUTPUT='//H5INT(1:ILAST)//
     * ' DSSFILE='//DSSFIL)
      WRITE (3,*)' CALLING H5B'
      CALL LASTCH ( H5INT, 17, JLAST)
      CALL EXPROG('H5B*H5B INPUT=IT2 OUTPUT=+'//H5INT(1:JLAST)//
     * ' DSSFILE='//DSSFIL)
      CALL ASIGNI ( 6, 3, 0, ISTAT)
C
C     IF NO C=FREQ-FLOW PART WAS FOUND, EXECUTE ONLY EAD
C
  450 CONTINUE
      WRITE (3,*)' CALLING EAD'
      IF(ICNT.EQ.1)THEN
      CALL LASTCH ( EADINT, 17, KLAST)
      CALL EXPROG('EAD*EADX INPUT=EADBASE OUTPUT='//EADINT(1:KLAST)//
     * ' TAPE71='//DSSFIL)
      CALL ASIGNI ( 6, 3, 0, ISTAT)
      ELSE
      CALL LASTCH ( EADINT, 17, KLAST)
      CALL EXPROG('EAD*EADX INPUT=EADPLAN OUTPUT='//EADINT(1:KLAST)//
```

```
     * ' TAPE71='//DSSFIL)
      CALL ASIGNI (6, 3, 0, ISTAT)
      ENDIF
C
C     OPEN FILES 110,111,112,120,121 AGAIN
C
      OPEN(UNIT=110,FILE=T110)
      CALL WIND(110)
      OPEN(UNIT=111,FILE=T111)
      CALL WIND(111)
      OPEN(UNIT=112,FILE=T112)
      CALL WIND(112)
      OPEN(UNIT=114,FILE=T114)
      CALL WIND(114)
      OPEN(UNIT=121,FILE=T121)
      CALL WIND(121)
      OPEN(UNIT=120,FILE=T120)
      CALL WIND(120)
C
C
C
C ----------------------------------------------------------------------------
C
C     IF THIS IS THE FIRST ITERATION, READ BASE CONDITION DAMAGES
C     FROM DSS
C
C
      IF(ICNT.EQ.1) THEN
      DO 455 I=1,6
      NSTATS(I) = -32
  455 CONTINUE
      CALL ZGPNP (BASEZ,A,B,C,D,E,F,NSTATS)
      IF (NSTATS(1).GE.0) NA = NSTATS(1)
      IF (NSTATS(2).GE.0) NB = NSTATS(2)
      IF (NSTATS(3).GE.0) NC = NSTATS(3)
      IF (NSTATS(4).GE.0) ND = NSTATS(4)
      IF (NSTATS(5).GE.0) NE = NSTATS(5)
      IF (NSTATS(6).GE.0) NF = NSTATS(6)
      CALL CHABLK (CPATH,1,80)
      CALL ZFPN(A,NA,B,NB,C,NC,D,ND,E,NE,F,NF,CPATH,NPATH)
C
      NARYLB=MARYLB
      NWBUFF=MWBUFF
      NWDATA=MWDATA
      JPLAN=MPLAN
      ICODE=1
C
      CALL ZGTPFD(IFLTAB,CPATH,NPATH,NREACH,N1ARY,JPLAN,IHORIZ,
     .C1UNIT,C2UNIT,C1TYPE,C2TYPE,CARYLB,NARYLB,IBUFF,NWBUFF,
     .DATA,NWDATA,ICODE,ISTAT)
C
      DO 457 IRCH=1,NREACH
      CALL A4TOCH(DATA(IRCH*2-1),1,6,CRCHNM(IRCH),1)
C
      DO 457 IPLN=1,JPLAN
      DUMMY(IRCH,IPLN) = DATA((IPLN+1)*NREACH+IRCH)
  457 CONTINUE
C
C
C     CORRECT DAMAGE ARRAY TO INCLUDE SITES WITH ZERO DAMAGES
C
      KCOUNT=0
      DO 459 I=1,NSITE
      IF(ISUB(I).NE.I) THEN
      KCOUNT = KCOUNT + 1
      DAMAGE(I) = DUMMY(KCOUNT,1)
      ELSE
      DAMAGE(I) = 0.
      ENDIF
  459 CONTINUE
C
      DBASE = 0.
      DO 460 I=1,NSITE
```

```
      DBASE = DBASE + DAMAGE(I)
  460 CONTINUE
C
C     BASE CONDITION DAMAGES ARE NOW CALLED DBASE
C
      ELSE
C     READ DAMAGES AT EACH SITE WITH CURRENT PLAN IMPLEMENTED
C
      DO 465 I=1,6
      NSTATS(I) = -32
  465 CONTINUE
      CALL ZGPNP (PLANZ,A,B,C,D,E,F,NSTATS)
      IF (NSTATS(1).GE.0) NA = NSTATS(1)
      IF (NSTATS(2).GE.0) NB = NSTATS(2)
      IF (NSTATS(3).GE.0) NC = NSTATS(3)
      IF (NSTATS(4).GE.0) ND = NSTATS(4)
      IF (NSTATS(5).GE.0) NE = NSTATS(5)
      IF (NSTATS(6).GE.0) NF = NSTATS(6)
      CALL CHABLK (CPATH,1,80)
      CALL ZFPN(A,NA,B,NB,C,NC,D,ND,E,NE,F,NF,CPATH,NPATH)
C
      NARYLB=MARYLB
      NWBUFF=MWBUFF
      NWDATA=MWDATA
      JPLAN=MPLAN
      ICODE=1
C
      CALL ZGTPFD(IFLTAB,CPATH,NPATH,NREACH,N1ARY,JPLAN,IHORIZ,
     .C1UNIT,C2UNIT,C1TYPE,C2TYPE,CARYLB,NARYLB,IBUFF,NWBUFF,
     .DATA,NWDATA,ICODE,ISTAT)
C
      DO 470 IRCH=1,NREACH
      CALL A4TOCH(DATA(IRCH*2-1),1,6,CRCHNM(IRCH),1)
C
      DO 470 IPLN=1,JPLAN
      DUMMY(IRCH,IPLN) = DATA((IPLN+1)*NREACH+IRCH)
  470 CONTINUE
C
C     CORRECT DAMAGE ARRAY TO INCLUDE SITES WITH ZERO DAMAGES
C
      JCOUNT=0
      DO 475 I=1,NSITE
      IF(ISUB(I).NE.I) THEN
      JCOUNT = JCOUNT + 1
      DAMAGE(I) = DUMMY(JCOUNT,2)
      ELSE
      DAMAGE(I) = 0.
      ENDIF
  475 CONTINUE
C
C
C
C     DAMAGES FOR THIS PLAN BY SITE ARE NOW IN DAMAGE ARRAY
C
C
      ENDIF
      ICNT=ICNT+1
C
C     CALL BENEFIT COST SUBROUTINE TO COMPUTE NET BENEFITS
C
C
      CALL NETBEN
C                                                                    ***********
C                                                                    * NETBEN *
C                                                                    ***********
C
C
      OBJFUN=TSNB
      RPLAN=DBASE-DPLAN
      WRITE(121,486) OBJFUN
  486 FORMAT(/5X,'THE OBJECTIVE FUNCTION IS . . . . . . . . . . .',
     .F10.2//)
C
```

```
      WRITE(121,490) DBASE,DPLAN,RPLAN,CPLAN,OBJFUN
C
C
C
  490 FORMAT(5X,'EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .'
     .F10.2,/
     .5X,'EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .',F10.2,/
     .5X,'EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .',F10.2,//
     .5X,'TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .',F10.2,/
     .5X,'EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .',F10.2/
     .80('_')/)
C
C
C     COMPARE TRIAL OPTIMUM WITH CURRENT OBJECTIVE FUNCTION
C                                                                    ............
C                                                                    .  COMPARE .
C                                                                    ............
C
C
C
C     IF THE NEW OBJECTIVE FUNCTION IS GREATER THAN THE TRIAL
C     OPTIMUM, SAVE THIS PLAN AS THE POTENTIAL OPTIMAL
C
  495 IF(OBJFUN.GT.TRIOPT) THEN
      DO 500 I=1,NSITE
      ISAVE(I)=IMEAS(I)
  500 CONTINUE
      SAVOPT=OBJFUN
      SVCOST=CPLAN
      SAVDAM=DPLAN
C
C     SAVE THE EAD OUTPUT FOR THE POTENTAIL OPTIMAL PLAN AS EADOUT
C     AND SAVE THE HEC5 OUTPUT AS HEC5OUT
C
      CLOSE(UNIT=122)
      CLOSE(UNIT=123)
      CALL CDELET('EADOUT',IERR)
      IF(IERR.EQ.0.OR.IERR.EQ.21)THEN
      CALL CRENAM(EADINT,'EADOUT',IERR)
      OPEN(UNIT=122,FILE=EADINT)
      ELSE
      ENDIF
      CALL CDELET('HEC5OUT',IERR)
      IF(IERR.EQ.0.OR.IERR.EQ.21) THEN
      CALL CRENAM(H5INT,'HEC5OUT',IERR)
      OPEN(UNIT=123, FILE=H5INT)
      ELSE
      ENDIF
      ELSE
      ENDIF
C
C     IF TRIAL OPTIMUM IS LESS THAN OBJECTIVE FUNCTION (TSNB)
C     A BETTER PLAN HAS BEEN IDENTIFIED.  SET TRIOPT = OBJFUN.
C
C
C
  600 IF(TRIOPT.LT.OBJFUN) THEN
       WRITE(121,604)
      WRITE(121,605)OBJFUN,TRIOPT
      TRIOPT=OBJFUN
      WRITE(121,610)TRIOPT
      ELSE
      WRITE(121,604)
      WRITE(121,615)OBJFUN,TRIOPT
      WRITE(121,620)
      ENDIF
  604 FORMAT(/5X,'COMPARE',/)
  605 FORMAT(/80('.')/5X,'OBJECTIVE FUNCTION (',F10.2,') IS GREATER THAN
     . TRIAL OPTIMUM (',F10.2,')'/)
  610 FORMAT(5X,'SET NEW TRIAL OPTIMUM TO ',F10.2/80('.')/)
  615 FORMAT(/80('.')/5X,'OBJECTIVE FUNCTION (',F10.2,') IS LESS THAN TR
     .IAL OPTIMUM (',F10.2')'/)
  620 FORMAT(5X,'DO NOT UPDATE TRIAL OPTIMUM')
```

```
C
C
C     EVALUATE SUBSET BOUND
C     IF BOUND WAS PREVIOUSLY COMPUTED, GO TO NEXT D/S SITE
C
  650 DO 670 I=1,KSITE
      IF(IMEAS(I).EQ.KMEAS(I).AND.KSITE.EQ.KBOUND)GO TO 770
  670 CONTINUE
C                                                               .................
C                                                               .    EVALUATE   .
C                                                               .  SUBSET BOUND .
C                                                               .................
C
C
C
C     SUM DAMAGES AND COSTS  DOWN TO KSITE
C
C
C
  728 SUMD=0.
      SUMC=0.
      DO 730 K=1,KSITE
         SUMD = SUMD + DAMAGE(K)
         SUMC = SUMC + COST(K)
  730 CONTINUE
      DAMAGE(KSITE) = SUMD
      COST(KSITE) = SUMC
C
C     SUBSET BOUND = BASE CONDITION DAMAGES FOR ENTIRE SYSTEM - DAMAGES WITH
C     MEASURES IMPLEMENTED TO KSITE - COSTS OF MEASURES TO KSITE
C
C
      BOUND = DBASE - SUMD - SUMC
C
      KBOUND=KSITE
      DO 739 I=1,KSITE
      KMEAS(I) = IMEAS(I)
  739 CONTINUE
C
  738 IF (KSITE.LT.NSITE)THEN
      WRITE(121,755)
      DO 740 I=1,KSITE
      WRITE(121,757)I,IMEAS(I)
  740 CONTINUE
      WRITE(121,758) BOUND
      ENDIF
  755 FORMAT(10X,'EVALUATE SUBSET BOUND'/5X,'SUBSET INCLUDES THE FOLLOWI
     .NG SITES:'/)
  757 FORMAT(10X,' SITE =',I2,5X,'MEASURE =',I2,)
  758 FORMAT(10X,' BOUND ='F10.2/)
C                                                            ....................
C                                                            .  CONSIDER NEXT   .
C                                                            . DOWNSTREAM SITE  .
C                                                            ....................
C
C
C
C
C     IF THE SUBSET BOUND IS GREATER THAN THE TRIAL OPTIMUM FURTHER SUBDIVIDE
C     SUBSET AND CONSIDER NEXT DOWNSTREAM SITE
C
C
C
C
  760 IF(BOUND.LE.TRIOPT) THEN
      IF(KSITE.LT.NSITE) WRITE(121,775)
       GO TO 790
       ENDIF
C
      WRITE(121,765)BOUND,TRIOPT
  765 FORMAT(5X,'BOUND (',F10.2,')IS GREATER THAN TRIAL OBJECTIVE FUNCTI
     .ON (',F10.2,').'/5X,'FURTHER DIVIDE SUBSET'//)
      ISITE = ISITE + 1
```

```
  770 KSITE = KSITE + 1
  775 FORMAT('BOUND IS LESS THAN TRIAL OPTIMUM. ELIMINATE SUBSET')
C
C
C     IF THIS IS THE LAST SITE, GO TO MODIFY PLAN
C
C
      IF(KSITE.EQ.NSITE) GO TO 800
C
C
C     IF THIS IS NOT THE LAST SITE, EVALUATE SUBSET BOUND
C     SUM DAMAGES AND COSTS OF LAST SIMULATION DOWN TO KSITE
C
C
C
      GO TO 650
C
C
C     IF BOUND IS LESS THAN TRIAL OPTIMUM, ELIMINATE SUBSET
C     AND LOOK FOR NEXT MEASURE AT THIS SITE (NEW SUBSET)
C
C                                                            ....................
C                                                            . ELIMINATE SUBSET .
C                                                            ....................
C
C
C     IF THERE IS ANOTHER MEASURE ADD IT
C
C                                                                 ...............
C                                                                 . MODIFY PLAN .
C                                                                 ...............
C
  790 CONTINUE
C
  800 REWIND 111
  805 READ(111,'(A80)',END=810) CARD
      IF(CARD(1:4).NE.AC) GO TO 805
      READ(CARD(11:14),'(2I2)') JSITE,JMEAS
      IF(JSITE.EQ.KSITE.AND.JMEAS.GT.IMEAS(KSITE)) THEN
         IMEAS(KSITE) = IMEAS(KSITE) + 1
         GO TO 1000
         ELSE
      GO TO 805
      ENDIF
  810 CONTINUE
C
C
C     IF THERE IS NO OTHER MEASURE, BACTRACK
C     ELIMINATE MEASURE FOR CURRENT SITE AND RECONSIDER PREVIOUS SITE
C
C
C
C                                                                  ..............
C                                                                  . BACKTRACK  .
C                                                                  ..............
      IMEAS(KSITE)=1
      KSITE = KSITE-1
C     IF THERE IS NO SUCH SITE, STOP
      IF(KSITE.EQ.0) GO TO 1200
C
C
C
C     IF PREVIOUS SITE EXISTS, GO TO MODIFY PLAN
C
C
      GO TO 800
C
C
C
C     CHECK FOR COMPLETE PLAN
C     IF THIS IS NOT THE LAST SITE, GO TO NEXT SITE AND ADD FIRST MEASURE
C
C
```

```
C                                                               ................
C                                                               .  CHECK FOR   .
C                                                               .COMPLETE PLAN .
C                                                               ................
C
 1000 IF(ISITE.LT.NSITE) THEN
         ISITE = ISITE + 1
         GO TO 1000
      ELSE
      ENDIF
C
C
C
C
C     IF THIS IS THE LAST SITE COMPLETE PLAN HAS BEEN FORMULATED
C     EVALUATE SYSTEM OBJECTIVE FUNCTION
      IF(ISITE.EQ.NSITE) GO TO 100
C
C                                                                  .............
C                                                                  . TERMINATE .
C                                                                  .............
C
C
 1200 CALL BANNER
C
      CALL BBOUT
      CLOSE(UNIT=111)
      CLOSE(UNIT=110)
      CLOSE(UNIT=112)
      CLOSE(UNIT=114)
      CLOSE(UNIT=120)
      CLOSE(UNIT=121)
      CLOSE(UNIT=122)
      CLOSE(UNIT=123)
      CALL ZCLOSE(IFLTAB)
 6000 STOP
      END
      SUBROUTINE BANNER
C ******************************************************************************
C *                                                                            *
C *   SUBROUTINE BANNER : WRITE OUT BANNER PAGE                                *
C *                                                                            *
C ******************************************************************************
C
      CHARACTER*80 CARD
      REWIND 120
      WRITE(120,10)
   10 FORMAT ('1',55('*'),38X,38('*')/
     .1X,'*  BRANCH-AND-BOUND ENUMERATION PROGRAM               *',38X,
     .'*  U. S. ARMY CORPS OF ENGINEERS     *'/
     .1X,'*  VERSION OF OCTOBER 1986                            *',38X,
     .'*  THE HYDROLOGIC ENGINEERING CENTER *'/
     .1X,'*                                                     *',38X,
     .'*  609 SECOND STREET                 *'/
     .1X,'*                                                     *',38X,
     .'*  DAVIS, CALIFORNIA  95616-4687     *'/
     .1X,'*                                                     *',38X,
     .'*  (916) 440-2105 (FTS) 448-2105     *'/
     .1X,55('*'),38X,38('*') ///////)
C
      WRITE(120,20)
   20 FORMAT(
     .34X,54HBBBBBBB   RRRRRRRR        A       N      N     CCCCCCC
     .10H   H     H/
     .34X,54H      B   R      R       A A      N N    N    C
     .10H   H     H/
     .34X,54H      B   R      R      A   A     N  N   N   C
     .10H   H     H/
     .34X,54HBBBBBBB   RRRRRRRR     AAAAAAA    N   N  N   C
     .10H   HHHHHHH/
     .34X,54H      B   R   R        A     A    N    N N   C
     .10H   H     H/
     .34X,54H      B   R    R       A     A    N     NN    C
```

```
     .10H   H     H/
     .34X,54HBBBBBBB   R       R     A      A    N      N      CCCCCCC
     .10H   H     H/)
C
C     WRITE HEADING FOR BRANCH-AND-BOUND PROGRAM
      WRITE(120,35)
   35 FORMAT('1',41('+')/,
     .1X,'+  BRANCH-AND-BOUND ENUMERATION PROGRAM +'/
     .1X,'+  VERSION DATE:      OCTOBER 31, 1986  +'/
     .1X,41('+')////,
     .1X,'***** INPUT LISTING *****'///)
C
C     WRITE INPUT LISTING TO OUTPUT
C
      REWIND 110
  100 READ(110,110,END=105) CARD
      WRITE(120,112) CARD
      GO TO 100
  105 CONTINUE
  110 FORMAT(A80)
  112 FORMAT(1X,A80)
      WRITE(120,200)
  200 FORMAT(///'***** END OF INPUT LISTING *****')
      RETURN
      END
      SUBROUTINE BBOUT
C
C ******************************************************************************
C *                                                                            *
C *     SUBROUTINE BBOUT :   PRINTS SUMMARY OUTPUT TABLE                       *
C *                                                                            *
C ******************************************************************************
C
C -----------------------------------------------------------------------------
      PARAMETER(MSITE=11)
      COMMON/SITE/NSITE,NMEAS,NPLAN
      COMMON/ECON/COST,DAMAGE,TSNB,DBASE,SUMC,SUMD,CPLAN,DPLAN
      COMMON/OPT/ISAVE,IMEAS,KMEAS
      COMMON/KEEP/SAVOPT,SVCOST,SAVDAM
      COMMON/TABLE/NPRINT
      CHARACTER*80 CARD,POUT
      DIMENSION COST(MSITE), DAMAGE(MSITE), ISAVE(MSITE),
     .IMEAS(MSITE), KMEAS(MSITE), NUMBER(MSITE)
C
C -----------------------------------------------------------------------------
C     COUNT NUMBER OF MEASURES AT EACH SITE AND TOTAL NUMBER OF PROPOSED
C     MEASURES
C
      REWIND 111
      DO 50 ISITE=1,NSITE
      NUMBER(ISITE)=0
   50 CONTINUE
      ISITE=1
      NMEAS=0
   70 READ(111,'(A80)',END=80)CARD
      IF(CARD(1:2).EQ.'*A')THEN
      READ(CARD(11:14),'(2I2)')ISITE,IMEAS(ISITE)
      NUMBER(ISITE) = NUMBER(ISITE) + 1
      NMEAS = NMEAS +1
      ELSE
      ENDIF
      GO TO 70
   80 CONTINUE
      REDUCE = DBASE - SAVDAM
      WRITE(120,200)
  100 WRITE(120,220) NSITE,NMEAS
      DO 130 ISITE=1,NSITE
      WRITE(120,240) ISITE,NUMBER(ISITE)
  130 CONTINUE
      WRITE(120,250) NPLAN
      WRITE(120,260) SAVOPT
      DO 150 I=1,NSITE
      WRITE(120,280)I,ISAVE(I)
```

```
  150 CONTINUE
  160 WRITE(120,300)DBASE,SAVDAM,REDUCE,SVCOST,SAVOPT
  200 FORMAT('1',////15X,37('*')/15X,('*'),35X,('*')/15X,
     .'*  BRANCH-AND-BOUND SUMMARY OUTPUT  *'/15X,('*'),35X('*')/
     .15X,37('*'))
  220 FORMAT(///5X,'SYSTEM SUMMARY'/5X,14('_')//
     .5X,'NUMBER OF SITES IN SYSTEM . . . . . . . .',I2//
     .5X,'TOTAL NUMBER OF MEASURES PROPOSED . . . .',I2//)
  240 FORMAT(10X,'MEASURES PROPOSED AT SITE ',I2,' . . . .',I2/)
  250 FORMAT(5X,'NUMBER OF PLANS ENUMERATED. . . . . . . .',I2)
  260 FORMAT(///5X,'ECONOMIC SUMMARY OF OPTIMUM PLAN'/5X,32('_')//
     .5X,'THE MAXIMUM OBJECTIVE FUNCTION IS. . . . . . . ',F10.2//
     .5X,'THE OPTIMAL PLAN INCLUDES THE FOLLOWING MEASURES :'/)
  280 FORMAT(7X,'SITE ',I2,5X,'MEASURE ',I2/)
  300 FORMAT(5X,'EXPECTED ANNUAL DAMAGES - EXISTING SYSTEM . . .'
     .F10.2,/
     .5X,'EXPECTED ANNUAL DAMAGES - PROPOSED SYSTEM . . .',F10.2,/
     .5X,'EXPECTED ANNUAL DAMAGE REDUCTION. . . . . . . .',F10.2,//
     .5X,'TOTAL SYSTEM ANNUAL COST. . . . . . . . . . . .',F10.2,/
     .5X,'EXPECTED ANNUAL SYSTEM NET BENEFITS . . . . . .',F10.2,)
  310 IF(NPRINT.EQ.2)THEN
      WRITE(120,380)
      REWIND 121
  320 READ(121,'(A80)',END=350)POUT
      WRITE(120,355)POUT
      GO TO 320
      ENDIF
  350 CONTINUE
      WRITE(120,390)
  355 FORMAT(1X,A80)
  380 FORMAT('1',//6X,50('*')/6X,('*'),48X,('*'),/6X,('*'),
     .'  INTERMEDIATE OUTPUT OF ALL PLANS ENUMERATED ',2X,('*')/
     .6X,('*'),48X,('*'),/6X,50('*')/)
  390 FORMAT(5X,'***** END OF BRANCH-AND-BOUND OUTPUT *****',/'1')
C
C
      RETURN
      END
      SUBROUTINE EADIN1(
     .IHEAD, NSTATS, IFLTAB)
C ******************************************************************************
C *                                                                            *
C *   EADIN1  :   READS THE MASTER INPUT FILE FOR THE BASE CONDITION           *
C *   PLAN AND CREATES A BASE EAD FILE (EADBASE) AND WRITES BASE CONDITION     *
C *   FLOW-FREQUENCY CURVES TO DSS                                             *
C *                                                                            *
C *   THIS ROUTINE READS FROM TAPE12 (DATA2) AND WRITES TO TAPE113 (EADBASE)
C *   AND DSS.
C *                                                                            *
C ******************************************************************************
C
C
C ------------------------------------------------------------------------------
C
      PARAMETER(MFRACT=18, MREC=30, MSITE=11, MMEAS=5)
      DIMENSION IDS(6), JDS(6)
      DIMENSION QF(40), QD(40)
      DIMENSION IHEAD(*), NSTATS(*), IFLTAB(*),
     .FRACT(MFRACT), WHOLE(MFRACT)
      COMMON/Z/BASEZ,PLANZ
      COMMON/SITE/NSITE,NMEAS,NPLAN
      COMMON/BR/IBR
      CHARACTER*80 IBR(MREC,MSITE,MMEAS)
      CHARACTER*32 A,B,C,D,E,F
      CHARACTER*3 IDS
      CHARACTER*3 JDS
      CHARACTER*80 CPATH, ZRCARD,BASEZ,PLANZ
      CHARACTER*80 TCARD,CARD,ZR,ZW,ZWQF
      CHARACTER*8 TMPFR
      CHARACTER*6 TMPRN
      LOGICAL IF
      LOGICAL RDZR
      DATA IDS/'T1','T2','T3','ID','DF','ZR'/
```

```
      DATA JDS/'TT','TT','TT','RN','FR','ZR'/
C
C ----------------------------------------------------------------------
      OPEN(UNIT=113,FILE='EADBASE')
      REWIND 112
      RDZR = .FALSE.
  100 READ (112,'(A80)',END=447)CARD
C
C     READ T1,T2,T3, ID,ZR AND DF RECORDS FROM HEC-5 AND CREATE TT,CN,RN
C     ZR AND FR RECORDS FOR EAD
C
      DO 440 K=1,6
      IF(CARD(1:2).NE.IDS(K)) GO TO 440
      CARD(1:2)=JDS(K)
C
C     MULTIPLY FREQUENCIES ON FR RECORD BY 100 (CONVERT FROM DECIMAL FORM TO
C     WHOLE NUMBER)
C
      IF(CARD(1:2).EQ.'RN')THEN
      TMPRN=CARD(3:8)
      GO TO 100
      ENDIF
      IF(CARD(1:2).EQ.'FR')THEN
      READ(CARD(3:8),'(I6)') M
      IF(M.EQ.19) M=18
      IF(M.LE.9)THEN
      READ(CARD,'(8X,9F8.0)') (FRACT(I),I=1,M)
      ELSE
      IF(M.EQ.10)THEN
      READ(CARD,'(8X,9F8.0)') (FRACT(I),I=1,9)
      READ(112,'(A80)',END=440)CARD
      READ(CARD,'(2X,F6.0)') FRACT(10)
      ELSE
      READ(CARD,'(8X,9F8.0)') (FRACT(I),I=1,9)
      READ(112,'(A80)',END=440)CARD
      READ(CARD,'(2X,F6.0,8F8.0)')(FRACT(I),I=10,M)
      ENDIF
      ENDIF
      DO 435 I=1,M
      WHOLE(I)=FRACT(I)*100
  435 CONTINUE
      IF(M.LE.8)THEN
      IF(RDZR) WRITE(113,'(2HER)')
      WRITE(113,'(2HRN,A6)')TMPRN
      WRITE(113,'(2HFR,A6,I8,8F8.2)')TMPRN,M,(WHOLE(I),I=1,M)
      ELSE
      IF(RDZR) WRITE(113,'(2HER)')
      WRITE(113,'(2HRN,A6)')TMPRN
      IF(M.EQ.9)THEN
      WRITE(113,'(2HFR,A6,I8,8F8.2)') TMPRN,M,(WHOLE(I),I=1,8)
      WRITE(113,'(2HFR,F6.2)') WHOLE(9)
      ELSE
      WRITE(113,'(2HFR,A6,I8,8F8.2)') TMPRN,M,(WHOLE(I),I=1,8)
      WRITE(113,'(2HFR,F6.2,8F8.2)') (WHOLE(I),I=9,M)
      ENDIF
      ENDIF
      ELSE
      WRITE(113,'(A80)')CARD
      IF(K.EQ.3) WRITE(113,445)
      IF(CARD(1:2).EQ.'ZR') RDZR=.TRUE.
      ENDIF
      IF(CARD(1:2).EQ.'ZR') RDZR=.TRUE.
      GO TO 100
  440 CONTINUE
      GO TO 100
  447 CONTINUE
  445 FORMAT('CN     1ALL CATE'/'PN      1  BASE CONDITION')
C
C ----------------------------------------------------------------------
C     BEGIN WRITE TO DSS
C
C     BASE CONDITION FLOW-FREQUENCY WAS WRITTEN TO DSS BY HEC5
C
```

```
C     WRITE BASE CONDITION FLOW-DAMAGE RELATIONSHIP TO DSS
C     FIRST, WRITE FLOWS INTO QD ARRAY
C
      REWIND 112
  480 READ(112,'(A80)',END=970) CARD
      IF(CARD(1:2).EQ.'DQ') GO TO 500
      GO TO 480
  500 READ(CARD,'(2X,I6)')M
      IF(M.LE.9)THEN
      READ(CARD,'(8X,9F8.0)') (QD(I),I=1,M)
      ELSEIF(M.EQ.10)THEN
      READ(CARD,'(8X,9F8.0)') (QD(I),I=1,9)
      READ(112,'(A80)',END=970) CARD
      READ(CARD,'(2X,F6.0)') QD(10)
      ELSE
      READ(CARD,'(8X,9F8.0)') (QD(I),I=1,9)
      READ(112,'(A80)',END=970)CARD
      READ(CARD,'(2X,F6.0,9F8.0)') (QD(I),I=10,M)
      ENDIF
C
C
C
C     ADD DAMAGES FROM DC RECORD.
C
      READ(112,'(A80)',END=970) CARD
      IF(M.LE.9) THEN
      READ(CARD,'(8X,9F8.0)') (QD(I),I=M+1,M+M)
      ELSEIF(M.EQ.10) THEN
      READ(CARD,'(8X,9F8.0)') (QD(I),I=11,19)
      READ(112,'(A80)',END=970) CARD
      READ(CARD,'(2X,F6.0)') QD(20)
      ELSE
      READ(CARD,'(8X,9F8.0)') (QD(I),I=M+1,M+9)
      READ(112,'(A80)',END=970) CARD
      READ(CARD,'(2X,F6.0,9F8.0)') (QD(I),I=M+10,35)
      ENDIF
C
C
C     LOOK FOR PATH NAME PARTS ON FIRST ZR RECORD
C
  600 READ(112,'(A80)',END=970)CARD
      IF(CARD(1:2).EQ.'ZR') THEN
      ZRCARD=CARD
C
      DO 800 I=1,6
      NSTATS(I) = -32
  800 CONTINUE
C
      CALL ZGPNP(ZRCARD,A,B,C,D,E,F,NSTATS)
      IF (NSTATS(1).GE.0) NA = NSTATS(1)
      IF (NSTATS(2).GE.0) NB = NSTATS(2)
      IF (NSTATS(3).GE.0) NC = NSTATS(3)
      IF (NSTATS(4).GE.0) ND = NSTATS(4)
      IF (NSTATS(5).GE.0) NE = NSTATS(5)
      IF (NSTATS(6).GE.0) NF = NSTATS(6)
C
C     TEST C PART
C     IF THE C PATH NAME IS FLOW-DAMAGE, WRITE TO DSS
C     IF THE C PATH NAME IS NOT, READ NEXT CARD ZRCARD
C
      IF(C(1:NC).NE.'FLOW-DAMAGE')GO TO 600
C
      IHEAD(1)=2
      IHEAD(2)=30
      IHEAD(3)=M
      IHEAD(4)=1
      IHEAD(5)=1
      IHEAD(6)=1
      CALL CHABLK(CPATH,1,80)
      CALL ZFPN(A,NA,B,NB,C,NC,D,ND,E,NE,F,NF,CPATH,NPATH)
      CALL CHTOA4('CFS     ',1,8,IHEAD(7),1)
      CALL CHTOA4('DOLLARS ',1,8,IHEAD(11),1)
      CALL CHRHOL('UNT ',1,4,IHEAD(15),1)
```

```
      CALL CHRHOL('UNT ',1,4,IHEAD(12),1)
      NDATA=M*4
      CALL ZWRITE(IFLTAB,CPATH,NPATH,IHEAD,30,QD,NDATA,0,LF)
C
      ENDIF
      GO TO 480
  970 CONTINUE
C
C
C     WRITE TO DSS IS COMPLETE
C -----------------------------------------------------------------------------
C
C
C     READ ZW RECORDS
C
      REWIND 112
  980 READ(112,'(A80)',END=1000)CARD
      IF(CARD(1:3).EQ.'ZW ')THEN
      CALL LASTCH(CARD,80,ILAST)
      ILAST = ILAST + 2
      CARD(ILAST:) = 'F=BASE'
      WRITE(113,'(A80)')CARD
      BASEZ=CARD
      GO TO 1100
      ELSE
      GO TO 980
      ENDIF
C
 1000 CONTINUE
 1100 WRITE(113,1200)
 1200 FORMAT('EJ')
      CLOSE(UNIT=113)
 1999 RETURN
      END
C
      SUBROUTINE EADIN2(
     .IHEAD, NSTATS, IFLTAB)
C ******************************************************************************
C *                                                                            *
C *   EADIN2   :   ADDS DSS PATH NAMES FOR THE CURRENT PLAN TO THE BASE        *
C *   EAD FILE, CREATING EADPLAN   AND   PUTS COSTS OF MEASURES IN THIS        *
C *   PLAN (M$ RECORDS) INTO COST ARRAY                                        *
C *                                                                            *
C *   SUBROUTINE READS FROM TAPE112 (DATA2) AND TAPE113 (EADBASE) AND WRITES TO*
C *   TAPE114 (EADPLAN)                                                        *
C *                                                                            *
C ******************************************************************************
C
C ------------------------------------------------------------------------------
C
C
      PARAMETER(MREC=30, MSITE=11, MMEAS=5)
      COMMON/BR/IBR
      COMMON/Z/BASEZ,PLANZ
      COMMON/SITE/NSITE,NMEAS,NPLAN
      COMMON/ECON/COST,DAMAGE,TSNB,DBASE,SUMC,SUMD,CPLAN,DPLAN
      CHARACTER*80 IBR(MREC,MSITE,MMEAS)
      CHARACTER*80 CARD,ZWQF,ZW,BASEZ,PLANZ,ZRPLAN,CPATH,ZROLD
      CHARACTER*6 RNSAVE,BSAVE
      CHARACTER*32 A,B,C,D,E,F
      DIMENSION COST(MSITE), DAMAGE(MSITE), IFLTAB(*),
     .IHEAD(*), NSTATS(*)
      LOGICAL ICHECK
C
C ------------------------------------------------------------------------------
      OPEN(UNIT=114,FILE='EADPLAN')
      OPEN(UNIT=113,FILE='EADBASE')
      REWIND 113
      REWIND 114
      DO 50 K=1,NSITE
      COST(K)=0.
   50 CONTINUE
C
```

```
C
      LCOUNT=0
      ICOST=1
  100 READ(113,'(A80)',END=200)CARD
      LCOUNT=LCOUNT+1
      IF(LCOUNT.EQ.1) ZROLD =CARD
      IF(CARD(1:2).EQ.'EJ') GO TO 370
      IF(CARD(1:2).NE.'ER'.AND.CARD(1:3).NE.'ZW ')WRITE(114,'(A80)')CARD
      IF(CARD(1:2).EQ.'PN')THEN
      WRITE(114,250) NPLAN
      ELSE
      ENDIF
      IF(CARD(1:2).EQ.'RN') THEN
      READ(CARD(3:8),'(A6)') RNSAVE
C
      ENDIF
      IF(CARD(1:2).EQ.'ER'.OR.CARD(1:2).EQ.'ZW') GO TO 280
C     LOOK FOR ZR RECORDS FOR PROPOSED PLAN IN CURRENT
C     DATA2 FILE AND ADD TO EADPLAN
C
      GO TO 100
  200 CONTINUE
  250 FORMAT('PN     2  PLAN',I2)
  280 REWIND 112
      ICHECK=.TRUE.
C
C     SKIP ZR RECORDS FOR BASE CONDITIONS (THEY OCCUR AFTER THE DA RECORD)
C
  300 READ(112,'(A80)',END=360)CARD
      IF(CARD(1:2).EQ.'DA')THEN
      READ(112,'(A80)',END=400)CARD
      READ(112,'(A80)',END=400)CARD
      READ(112,'(A80)',END=400)CARD
      READ(112,'(A80)',END=400)CARD
      READ(112,'(A80)',END=400)CARD
      READ(112,'(A80)',END=400)CARD
      READ(112,'(A80)',END=400)CARD
      READ(112,'(A80)',END=400)CARD
      READ(112,'(A80)',END=400)CARD
      ELSE
      ENDIF
C
C     READ B PART OF EACH ZR RECORD FOR THE PLAN (THESE OCCUR BEFORE THE
C     DA RECORD
C
      IF(CARD(1:2).EQ.'ZR')THEN
      ZRPLAN=CARD
      DO 315 I=1,6
      NSTATS(I) = -32
  315 CONTINUE
      CALL ZGPNP (ZRPLAN,A,B,C,D,E,F,NSTATS)
      IF (NSTATS(1).GE.0) NA = NSTATS(1)
      IF (NSTATS(2).GE.0) NB = NSTATS(2)
      IF (NSTATS(3).GE.0) NC = NSTATS(3)
      IF (NSTATS(4).GE.0) ND = NSTATS(4)
      IF (NSTATS(5).GE.0) NE = NSTATS(5)
      IF (NSTATS(6).GE.0) NF = NSTATS(6)
      CALL CHABLK (CPATH,1,80)
      CALL ZFPN(A,NA,B,NB,C,NC,D,ND,E,NE,F,NF,CPATH,NPATH)
C
C     TEST B PART OF EACH ZR RECORD
C
C     ADD ZR RECORD TO EADPLAN AT THE SAME SITE
C
  350 BSAVE= B(1:NB)
      IF (BSAVE.EQ.RNSAVE) THEN
      IF (ICHECK) THEN
      WRITE(114,'(2HEP)')
      ICHECK=.FALSE.
      IF(ZROLD.NE.ZRPLAN) WRITE(114,'(A80)') ZRPLAN
      ELSE
      IF(ZROLD.NE.ZRPLAN) WRITE(114,'(A80)') ZRPLAN
      ENDIF
```

```
      ZROLD=ZRPLAN
      ENDIF
      ENDIF
      IF(CARD(1:2).EQ.'ED') THEN
      WRITE(114,'(2HER)')
      GO TO 100
      ENDIF
      GO TO 300
  360 CONTINUE
      GO TO 100
C
C     LOOK FOR M$ RECORDS IN DATA2 AND PUT INTO COST ARRAY
C
  365 WRITE(114,'(A80)') CARD
  370 REWIND 112
  375 READ(112,'(A80)',END=400)CARD
      IF(CARD(1:2).EQ.'M$')THEN
      READ(CARD,'(2X,F6.0)') COST(ICOST)
      ICOST=ICOST+1
      ENDIF
      IF(CARD(1:3).EQ.'ZW ')THEN
      CALL LASTCH(CARD,80,ILAST)
      ILAST = ILAST + 2
      CARD(ILAST:) = 'F=PLAN'
      PLANZ=CARD
      WRITE(114,'(A80)')CARD
      WRITE(114,'(2HEJ)')
      ENDIF
      GO TO 375
  400 CONTINUE
  420 CLOSE(UNIT=113)
      CLOSE(UNIT=114)
      RETURN
      END
      SUBROUTINE HEC5IN
C
C ******************************************************************************
C *                                                                            *
C *  HEC5IN   :      WRITES AN HEC-5 INPUT FILE FROM THE DATA2 FILE            *
C *                                                                            *
C *   SUBROUTINE READS FROM TAPE 112 (DATA2) AND WRITES TO TAPE 115 (HEC5DATA)
C *                                                                            *
C ******************************************************************************
C
C ------------------------------------------------------------------------------
C
      CHARACTER*80 CARD,ZW
      COMMON/COUNT/ICNT
      DATA IZR /'ZR'/
      OPEN(UNIT=115,FILE='HEC5DATA')
C
C ------------------------------------------------------------------------------
      REWIND 112
      REWIND 115
  100 READ(112,'(A80)',END=300)CARD
      IF(CARD(1:4).EQ.'ZWQF')THEN
      CALL LASTCH(CARD,80,ILAST)
      ILAST=ILAST+2
      IF(ICNT.EQ.1.) CARD(ILAST:)='F=BASE'
      IF(ICNT.GT.1) CARD(ILAST:)='F=PLAN'
      ENDIF
      IF(CARD(1:2).NE.'ZR'.AND.CARD(1:4).NE.'ZW '.AND.CARD(1:2).NE.
     .'M$')THEN
      WRITE(115,'(A80)')CARD
      ENDIF
      GO TO 100
  300 CONTINUE
      CLOSE(UNIT=115)
  999 RETURN
      END
      SUBROUTINE NETBEN
C
C ******************************************************************************
```

```
C *    SUBROUTINE NETBEN :  COMPUTES NET BENEFITS                                *
C *      TOTAL SYSTEM                                                             *
C *      NET BENEFITS = BASE CONDITION DAMAGES - COSTS - DAMAGES WITH PLAN        *
C *      TSNB = DBASE - CPLAN - DPLAN                                             *
C ******************************************************************************
C
C ------------------------------------------------------------------------------
      PARAMETER(MSITE=11)
      COMMON/ECON/COST,DAMAGE,TSNB,DBASE,SUMC,SUMD,CPLAN,DPLAN
      COMMON/SITE/NSITE,NMEAS,NPLAN
      DIMENSION COST(MSITE), DAMAGE(MSITE)
C
C ------------------------------------------------------------------------------
C
C     SUM COSTS AND DAMAGES FOR ALL SITES FOR CURRENT PLAN
C
      CPLAN=0.
      DPLAN=0.
C
      DO 100 I=1,NSITE
      CPLAN = CPLAN + COST(I)
      DPLAN = DPLAN + DAMAGE(I)
  100 CONTINUE
C
C
      TSNB = DBASE - CPLAN - DPLAN
C
  999 RETURN
      END
      SUBROUTINE PRE(
     .ISUB)
C **************************************************************************** *
C *                                                                            *
C *      PRE   :  PROCESSES A MASTER HEC-5 INPUT FILE INTO AN INTERMEDIATE     *
C *      FILE (CALLED DATA1)                                                   *
C *      THE DATA1 FILE HAS A *ADD RECORD IN PLACE OF EACH BLOCK OF DATA       *
C *      DESCRIBING PROPOSED ALTERNATIVES.                                     *
C *                                                                            *
C *                                                                            *
C *      SUBROUTINE READS USER INPUT AND WRITES TAPE 111 (DATA1).
C *                                                                            *
C ******************************************************************************
C
C ------------------------------------------------------------------------------
      PARAMETER(MREC=30, MSITE=11, MMEAS=5)
      COMMON/SITE/NSITE,NMEAS,NPLAN
      COMMON/BR/IBR
      COMMON/Z/BASEZ,PLANZ
      COMMON/TABLE/NPRINT
      CHARACTER*2 BBC,EBC,ERC
      CHARACTER*80 CARD,BASEZ,PLANZ
      CHARACTER*80 IBR(MREC,MSITE,MMEAS)
      DIMENSION ISUB(MSITE)
      LOGICAL BLK
      DATA BBC/'BB'/,EBC/'EB'/,ERC/'ER'/
C
C ------------------------------------------------------------------------------
C
C     INITIALIZE VARIABLES
C
      BLK = .FALSE.
      NOUT=0
C
C
  100 READ(110,105,END=720) CARD
  105 FORMAT(A80)
C
C
C
  200 IF (CARD(1:2).EQ.BBC) THEN
      READ (CARD(3:8),'(I6)') ISITE
      READ (CARD(9:16),'(I8)') IMEAS
      ICARD = 0
```

```
      BLK = .TRUE.
      NOUT=NOUT+1
      IF (NOUT.EQ.1) READ(CARD(79:80),'(I2)') NPRINT
      GO TO 100
  300 ENDIF
C
C
  400 IF (BLK) THEN
      ICARD = ICARD +1
      IBR(ICARD,ISITE,IMEAS) = CARD
  500 IF (CARD(1:2).EQ.EBC) THEN
      BLK = .FALSE.
      CARD = '*ADD,BLOCK'
      WRITE (CARD(11:14),'(2I2)') ISITE, IMEAS
      ELSE
      GO TO 100
  600 ENDIF
C
C
  700 ENDIF
      WRITE (111,'(A80)') CARD
      IF(CARD(1:2).NE.ERC) GO TO 100
  720 CONTINUE
      REWIND 111
C
C     PUT SITES WITH NO DAMAGE CENTERS INTO ISUB ARRAY
C     LATER A ZERO WILL BE INSERTED INTO THE DAMAGE ARRAY
C
  740 READ(111,'(A80)',END=780) CARD
      IF(CARD(1:4).EQ.'*ADD') THEN
      READ(CARD(11:12),'(I2)') ITEST
      READ(111,'(A80)',END=780) CARD
      IF(CARD(1:2).NE.'DA') THEN
      ISUB(ITEST) = ITEST
      ELSE
      ISUB(ITEST) = 0
      ENDIF
      ENDIF
      IF(CARD(1:2).NE.ERC) GO TO 740
  780 CONTINUE
C
  800 REWIND 111
  999 RETURN
      END
```