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FLOODPLAIN-MANAGEMENT PLAN ENUMERATION

By David T. Ford[1] and Allan Oto,[2] Members, ASCE

ABSTRACT: A branch-and-bound enumeration procedure improves the search for an optimal floodplain-management plan. The procedure considers all combinations of expert-defined alternative measures. However, through bounding, it eliminates inferior combinations without exhaustive detailed evaluation. In cases for which detailed evaluation is required, we propose using Hydrologic Engineering Center (HEC) system-simulation, economic-analysis, and data-management software. We demonstrate the procedure with an example.

PLAN-FORMULATION PROBLEM

Problem Definition

The problem addressed here is identification of the optimal management plan for a selected floodplain. The objective function is economically based: the optimal plan is the plan that yields maximum contribution to national economic development (NED). Colloquially, planners refer to this plan as the NED plan. The decision variables are the types, locations, and sizes of the damage-reduction measures included in the plan. Technical, financial, social, environmental, and political constraints must be satisfied.

Objective Function

The NED contribution of a floodplain-management plan is the net benefit of the plan. Guidelines for Federal water-resources planning [U.S. Water Resources Council (USWRC) 1983] define this as

$$NB = (B_L + B_I + B_{IR}) - C \quad (1)$$

in which NB = net benefit; B_L = location benefit; B_I = intensification benefit; B_{IR} = inundation-reduction benefit; and C = total cost of implementing and maintaining the plan. Location benefit is the increased net income of additional floodplain development due to the plan. Intensification benefit is the increased net income of existing floodplain activities. Inundation-reduction benefit is

$$B_{IR} = (D_{exist} - D_{\text{plan}}) \quad (2)$$

in which D_{exist} = existing-condition flood damage; and D_{plan} = flood damage with the plan in place. For Federal water-resources projects ". . . flood damages are the potential average annual dollar damages . . . estimated by using standard damage-frequency integration techniques and computer programs that relate hydrologic flood variables such as discharge and stage to damages and to the probability of occurrence of such variables (USWRC 1983)." Thus, the objective function becomes

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TABLE 1. Flood-Damage-Mitigation Measures

Measures that decrease level of flooding (1)	Measures that decrease damage susceptibility (2)	Measures that redistribute losses (3)
Discharge Reduction: Watershed management Weather modification Reservoir Natural storage improvement Floodway Diversion Depth Reduction: Channel-lining Channel-obstruction removal Channel-cross section increase Duration Reduction: Reservoir-operation improvement Local-drainage system improvement	Floodplain Management: Land-use regulation Urban renewal Government purchase of property Subsidized relocation Differential taxation Structure removal Floodproofing: Impervious-material construction Land elevation Construction on stilts Installation of floodshields Closure of backflow valves Levee or Floodwall Preparedness Planning: Flood warning and evacuation Protection of contents	Disaster relief Flood insurance Reconstruction grants Tax write-offs

Note: Adapted from Wood, Gooch, et al. (1985).

$$NB = B_L + B_I + [E(D_{exist}) - E(D_{plan})] - C \qquad (3)$$

in which $E[\cdot]$ denotes the average or expected annual value. The expected damage value is the integral of the cumulative probability distribution function (CDF) of annual damage.

Decision Variables

Solution of the formulation problem requires selection of appropriate measures and specification of the location and size of the facilities to maximize net benefit. Table 1 shows damage-mitigation measures that might be included. A floodplain-management plan comprises one or more of these measures. The cost and benefit of the plan is a function of the types, locations, and sizes of the measures.

SOLUTION TECHNIQUES

Techniques proposed for solution of the plan-formulation problem include (1) Enumeration-with-simulation; and (2) mathematical-programming.

Enumeration-with-Simulation Techniques

Enumeration-with-simulation techniques seek the optimal management plan by nominating iteratively trial plans and evaluating their efficiency. To evaluate a plan, the analyst simulates system response to flooding, given the type, location, and size of the measures. With the state of the system thus determined, solution of Eq. 1 determines the benefit. The optimal plan is the plan that yields greatest benefit of all those evaluated.

Bedient et al. (1985) describe an application of enumeration-with-simulation to develop a floodplain management plan for The Woodlands, Texas. They formulated approximately 40 candidate plans, based on experience and knowledge of technical, financial, social, environmental, and political constraints. They then used a catchment runoff model to evaluate land-use and detention alternatives and a fluvial hydraulics model to estimate flood-inundation depths with various channel configurations. Finally, after complete enumeration, they selected the optimal plan by comparison. This procedure is typical of current floodplain management planning.

Mathematical-Programming Techniques

Mathematical-programming techniques seek the optimal management plan via application of the calculus-based tools of operations research. Day (1970) presents a linear-programming model that identifies economically-efficient combinations of land-use controls, site elevation, and floodproofing. Mays and Bedient (1982) propose a dynamic-programming (DP) procedure for locating and sizing detention structures, given the catchment-runoff hydrographs. Bennet and Mays (1985) present a heuristic DP procedure to determine the minimum-cost detention and drainage channel system for a catchment. Davis (1975) and Lott (1976) combine simulation with nonlinear programming to identify optimal floodplain-management plans. Unfortunately, as Helweg et al. (1982) note, mathematical-programming procedures seldom are used in practical water-resources planning. One reason cited is that these procedures often do not permit sufficient flexibility in plan formulation.

Branch-and-Bound Enumeration

Ball, Bialas, and Loucks (1978) recognized the need for flexibility in plan formulation. They propose a branch-and-bound enumeration scheme that identifies the least-costly plan from candidates nominated by a planning expert (or group of experts). In their scheme, the expert identifies catchment sites at which measures may be implemented. For each site, the expert may propose: (1) Status quo; (2) alternative levees; (3) various flood-storage basins; (4) alternative reservoirs; and (5) various channel improvements. Each possible combination of one measure for each site constitutes a plan. The cost of each plan is a function of the measures included and the flow with these measures in place. A generalized routing model determines the flow.

To find the least-costly plan, the branch-and-bound procedure begins with the entire set of plans and successively divides the set into smaller subsets. The procedure tests the feasibility of and estimates a lower bound on the cost of the best plan in each subset. A plan is feasible if it protects specified land areas from a design storm. If plans in the subset are infeasible, or if the lower bound on cost exceeds the cost of the best plan known, the procedure eliminates the subset. Otherwise, the procedure further subdivides the set and repeats the evaluation.

BRANCH-AND-BOUND ENUMERATION PROCEDURE

Summary of Procedure

We propose a branch-and-bound enumeration procedure to identify the NED plan from a set of candidates nominated by a planning expert. This scheme is similar to that of Ball, Bialas, and Loucks, but it: (1) Permits analysis of any damage-mitigation option presented in Table 1; (2) uses maximum net benefit as the optimality criteria; and (3) accounts for hydrologic risk via expected-value analysis. Our proposed scheme finds the NED plan with the following steps:

1. Separate the plans in the set into mutually-exclusive subsets for evaluation. Select one of the subsets.
2. Determine, with Eq. 3, a bound on the maximum net benefit possible if the best plan in the subset is selected.
3. Determine the feasibility of plans in the subset. Compare the bound with the net benefit of the best plan known. If the subset plans are feasible, and if the bound exceeds the benefit of the best-known plan, the subset may include a better plan. In that case, go to step 4. Otherwise, eliminate all plans in the subset and backtrack. That is, select another subset, and go to step 2.
4. If possible, separate the subset further, and go to step 2. If further separation is not possible, backtrack. If all subsets have been evaluated or eliminated, stop.

Bowen (1987) discusses these steps and presents a detailed algorithm.

Benefit and Cost Evaluation

We propose evaluating the inundation-reduction benefit of Eq. 3 with the Hydrologic Engineering Center's (HEC) Expected Annual Flood Damage (EAD) computer program ("Expected" 1984a). The program derives and integrates the annual-damage CDF. To derive this CDF, the annual-maximum discharge CDF is transformed with an elevation-discharge function and an elevation-damage function, as illustrated by Fig. 1. Program input includes the discharge CDF, elevation-discharge, and elevation-damage functions for the location of interest.

Modifications to the discharge CDF, elevation-discharge, and elevation-damage functions characterize the impacts of management measures. We propose estimating the modifications with computer programs HEC-1 ("HEC-1" 1985), HEC-2 ("HEC-2" 1982), and SID ("Structure" 1987) and electronically transferring the results to the EAD program with the HEC data storage system, HEC-DSS ("Hydrologic" 1984b). Table 2 summarizes the capabilities of these programs. Table 3 shows program usage for damage-mitigation measure simulation. Fig. 2 shows the interrelationship of the HEC programs and the branch-and-bound algorithm. This interrelationship makes enumeration convenient. For example, to evaluate a proposed reservoir, the analyst prepares HEC-1 input describing the site, spillway, and outlet. Executing the program defines the modified discharge CDF, which is stored with HEC-DSS. Program EAD retrieves the CDF and other functions from HEC-DSS and computes the inundation-reduction benefit.

The cost in Eq. 3 includes capital cost, operation, maintenance, replacement, and repair cost, environmental-mitigation cost, and any other pertinent

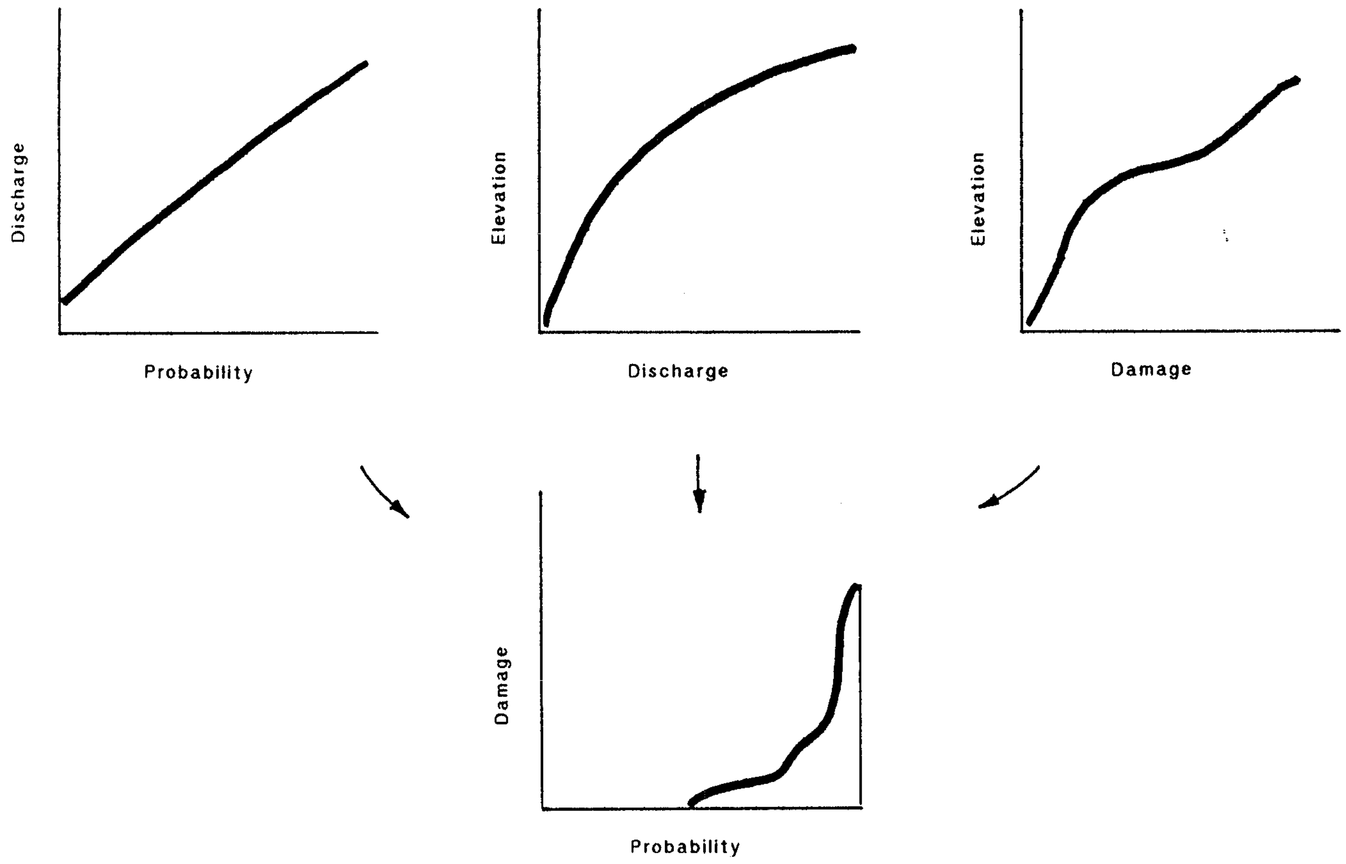

FIG. 1. Transformation for Expected Annual Damage Computation

TABLE 2. Summary of HEC Program Capabilities

Program (1)	Capabilities (2)
HEC-1	Simulates rainfall-runoff processes; accounts for flood-wave motion in catchment channels; models performance of detention structures, diversions, pumps; derives discharge CDF if hypothetical rainfall hyetographs or natural-condition runoff hydrographs given. Also computes expected-annual damage if elevation-discharge and elevation-damage function are specified.
HEC-2	Computes water-surface elevation for any point on natural or improved channel, given steady-state discharge; channel geometry and roughness user-defined; derives elevation-discharge function by repeated execution with arbitrarily-selected discharge values.
SID	Manipulates individual property elevation-damage functions to derive aggregated elevation-damage function; adjusts functions to model impacts of damage-reduction measures.
HEC-DSS	Stores, manipulates, retrieves, and displays results of simulation with other HEC programs.

project cost. These estimates may be based on historical data, detailed quantity and unit cost estimates, or parametric methods. Walski and Pelliccia (1981) and the United Nations (1972) present guidelines for developing reconnaissance or feasibility cost estimates. Because of regional cost variation and institutional procedural differences, we rely on the analyst to estimate the cost of each measure.

We rely on the analyst also to specify location and intensification benefits, if these are to be included. The USWRC guidelines suggest how the benefits may be evaluated (U.S. Water Resources Council 1983).

Example

We can demonstrate the proposed branch-and-bound scheme with the sim-

TABLE 3. Computer Programs for Evaluation of Flood-Damage-Mitigation Measures

Category of measure (see Table 1) (1)	HEC-1 for modified discharge-probability function (2)	HEC-2 for modified elevation-discharge function (3)	SID for modified elevation-damage function (4)
Discharge-reduction	X	—	—
Depth-reduction	X[a]	X	—
Duration-reduction	X	—	—
Floodplain management	X	—	—
Floodproofing	—	—	X
Levee/floodwall	X[a]	X	X
Preparedness planning	—	—	X[b]

[a] If floodplain storage altered significantly.
[b] Evaluation requires subjective analysis.

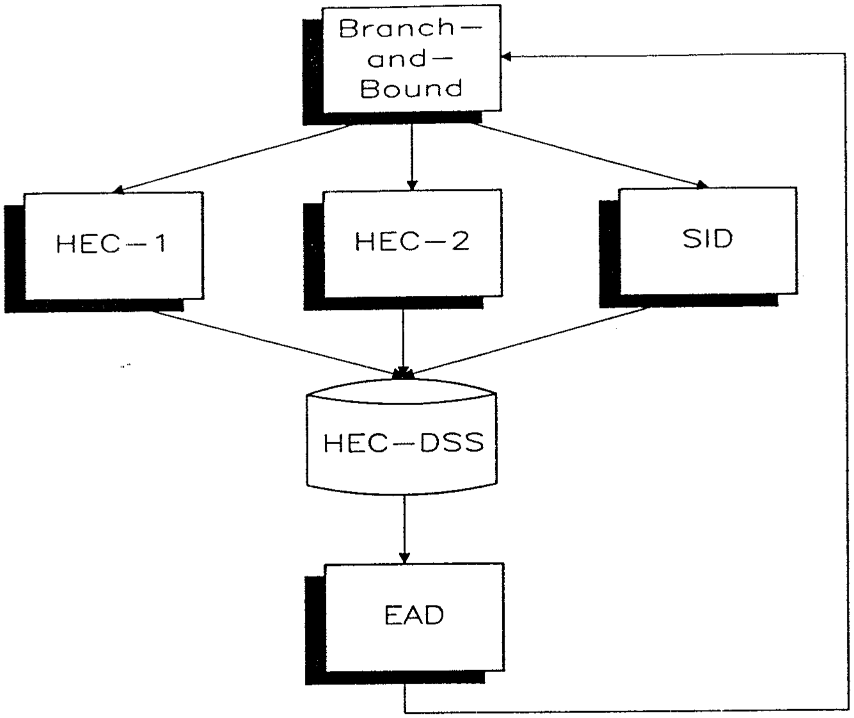

FIG. 2. Interrelationship of HEC Programs

ple floodplain shown in Fig. 3(*a*). To reduce the damage at sites A and B, an expert proposes a 2,500 acre-ft reservoir (R) or 40-ft wide channel improvement (CI) for site 1 and a 1,200-cfs diversion (D) or a 1,700-cfs levee (L) for site 2. Combining one measure for each site yields four possible plans. To compute the net benefit of any of these plans, Eq. 3 can be written as

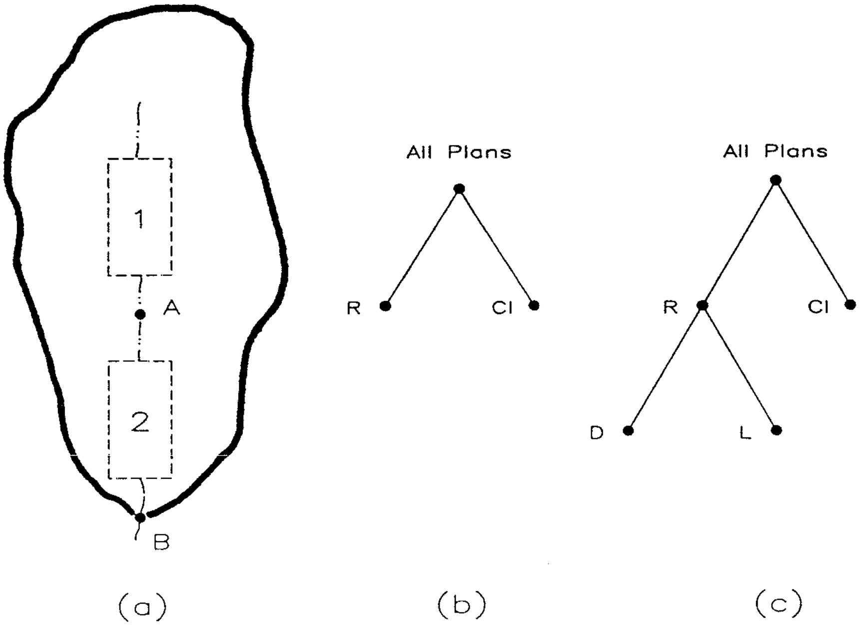

FIG. 3. (*a*) Two-Site System with (*b*) First Separation and (*c*) Second Separation

$$NB = B_L + B_I + E[D(A)_{exist}] - E[D(A)_{plan}] + E[D(B)_{exist}] - E[D(B)_{plan}] - C(1) - C(2) \quad (3a)$$

in which $E[D(\cdot)_{exist}]$ = expected annual existing-condition damage at the site; $E[D(\cdot)_{plan}]$ = expected annual damage at the specified site with the plan in place; and $C(\cdot)$ = cost of measure at the specified site. To solve Eq. 3*a*, we: (1) Execute the HEC programs to estimate inundation-reduction benefit; (2) add any specified intensification and location benefits; and (3) subtract the costs. The goal is to identify the NED plan without this detailed evaluation of all plans.

Initially, we separate the plans into the following mutually-exclusive subsets: (1) Plans that include the reservoir at site 1; and (2) plans that include channel improvement at site 1. Fig. 3(*b*) illustrates this. We select the subset that includes the reservoir for site 1 and estimate, with Eq. 3*a*, an upper bound on net benefit for all plans that include this reservoir. To do so, without knowing which measure is included for site 2, we assume the plan will include a perfect measure there. This hypothetical perfect measure has two important properties: (1) It eliminates all residual damage downstream of its location; and (2) it has no cost. With the hypothetical measure at site 2, $E[D(B)_{exist}] - E[D(B)_{plan}]$ and $C(2)$ in Eq. 3*a* equal zero. Simulation and EAD evaluation define $E[D(A)_{exist}]$ and $E[D(A)_{plan}]$. After adding location and intensification benefits and subtracting channel-improvement cost, the computed subset bound is \$20,000. With either of the real measures nominated for site 2, $E[D(B)_{exist}] - E[D(B)_{plan}]$ will exceed zero, or $C(2)$ will exceed zero. Therefore, the net benefit of any plan that includes the reservoir at site 1 will be less than \$20,000.

Next we separate the reservoir subset based on the measure included for site 2. Fig. 3(*c*) shows the separation. We chose the subset with the diversion. This step defines a complete plan; a measure is specified for each site. The net benefit, computed with Eq. 3*a*, is \$10,000. We tentatively declare this plan optimal.

When a subset cannot be separated further, the procedure backtracks to a subset not yet separated or evaluated. Thus, at this point in the example, we backtrack to the subset with the reservoir at site 1 and the levee at site 2. The net benefit of this subset, computed with Eq. 3*a*, is \$15,000. This exceeds the previous maximum, so we tentatively declare this plan optimal.

Next the procedure backtracks to consider plans with the channel improvement for site 1. With the hypothetical perfect measure for site 2, we estimate an upper bound on net benefit for all plans that include the channel improvement by solving Eq. 3*a*. In this case, the computed subset bound is \$7,000. With either of the real measures nominated for site 2, the net benefit will be less than this. As this is less than the net benefit of the best plan known, we infer that all plans with channel improvement are inferior to that best plan. Therefore, we eliminate them from further consideration.

Now we have evaluated or eliminated all plans. The NED plan includes the reservoir at site 1 and the levee at site 2.

APPLICATION

To illustrate further the branch-and-bound procedure, we use it to formulate a management plan for the floodplain shown in Fig. 4. In this case, the floodplain is protected by a major levee. However, the levee restricts runoff into the river, so the interior area may flood. This flooded area includes residential, commercial, and industrial development, and agricultural lands. Expected annual damage in the floodplain is $\$1165.83 \times 10^3$. For analysis, the damage is related to water-surface elevation at index points labeled 1030, 2030, and 305 in Fig. 4. Davis (1975) and the HEC ("Flood" 1977) published hydrologic, hydraulic, and economic data for the floodplain. We modified and adopted these for this example.

Measures Considered

Floodplain-management experts proposed alternative measures for three sites in the catchment, as shown in Fig. 4. Table 4 identifies the measures and provides cost estimates. A proposed reservoir reduces damage at locations 1030 and 305. A levee or diversion reduce damage at location 2030. A pump will limit ponding and reduce damage at location 305. Ideally, the experts would nominate such measures only after assessing hydrologic-economic-engineering information, social suitability, ecological impact, and community well-being effects. James, Benke, and Ragsdale (1978) offer guidance on integrating these considerations.

Plan-Evaluation Mechanics

With the measures proposed, we can formulate 45 alternative plans. Each of the plans includes one measure for each site. The goal is to identify the NED plan without evaluating all 45 alternatives.

The analysis begins with preparation of input to simulate and evaluate the existing condition with the selected software. In addition to developing existing-condition input, we prepare input-file fragments to describe each of the proposed measures. In the enumeration, we add these input-file fragments to the appropriate existing-condition input file to model the alternatives. For example, an HEC-1 input-file fragment with site-topographic data, spillway characteristics, and low-level outlet characteristics describes the proposed 2,500 acre-ft reservoir. When the reservoir is included in a trial plan, we add this fragment to the input and execute the program to compute the modified discharge CDF.

Results of Application

The optimal combination of the proposed floodplain management measures includes the 2,500 acre-ft reservoir (R25) and the 8,300-cfs levee (L83). Table 5 summarizes the iterations of the branch-and-bound procedure. Of the 45 possible plans, we evaluated explicitly only 13. Comparison of a computed bound with the trial-optimal objective function permitted elimination of the remaining 32.

We start with the 2,500 acre-ft reservoir (R25). The computed subset bound is $\$817.77 \times 10^3$. Next we subdivided this set and selected the subset with the 8,300-cfs levee (L83). The upper limit on plans that include R25 and L83 is 709.87 thousand. We further subdivided this subset and selected the subset that includes the 2,000-cfs pumping station (P20). This is our initial guess of the optimal combination. We combine HEC-1 input-file fragments with existing-condition input to model the plan. As shown for iteration 1c in Table 5, the annual net benefit is $\$465.20 \times 10^3$. This is a trial optimum

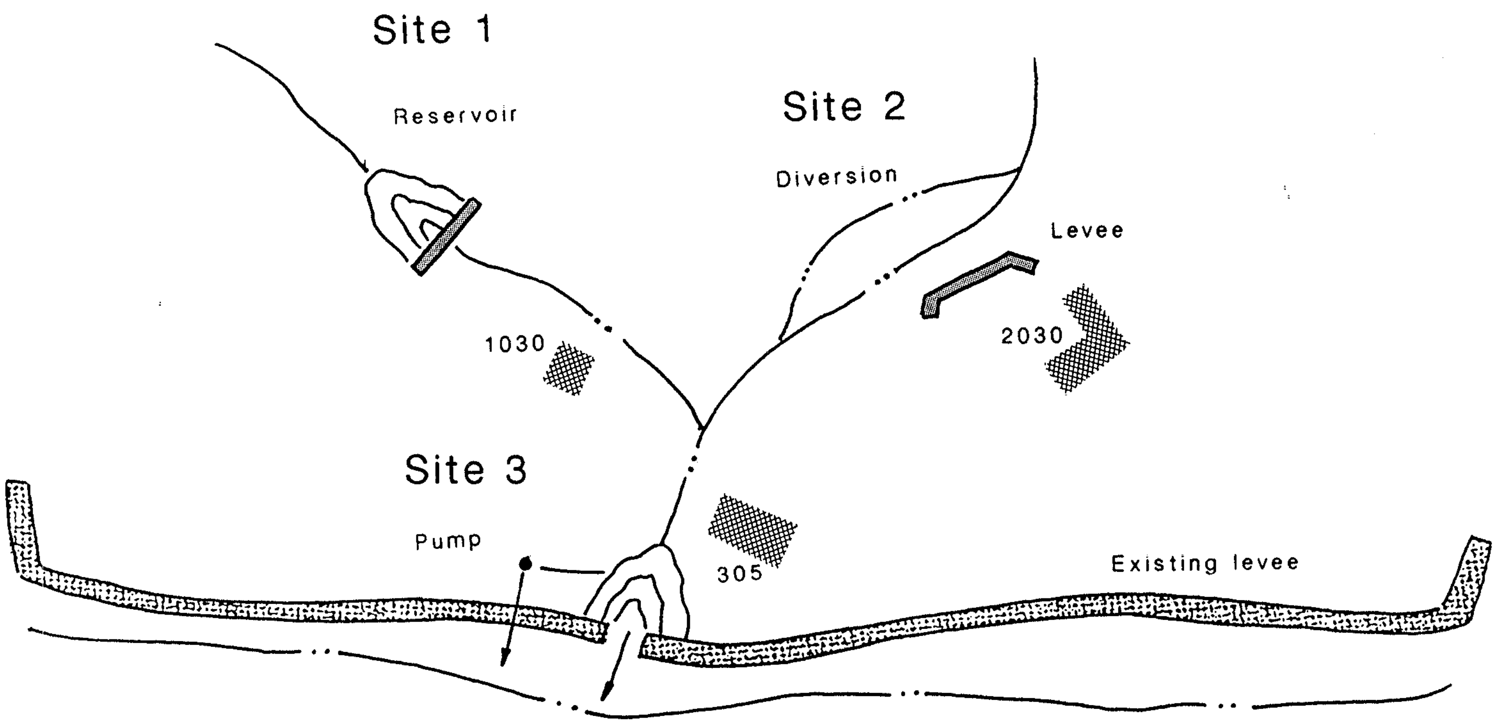

FIG. 4. Example Floodplain

TABLE 4. Measures Considered for Example

Measure (1)	Annual cost, in $1,000[a] (2)
SQ1 do nothing	0.00
R25 2,500 acre-ft reservoir	110.10
R68 6,800 acre-ft reservoir	514.24
SQ2 do nothing	0.00
D12 1,250 cfs diversion	98.10
D75 7,500 cfs diversion	340.08
L17 1,700 cfs levee	3.08
L83 8,300 cfs levee	20.77
SQ3 do nothing	0.00
P10 1,000 cfs pump	117.44
P20 2,000 cfs pump	168.82

[a] This total annual cost includes annual-equivalent capital cost plus annual operation, maintenance, replacement, and repair cost.

with which other solutions and bounds will be compared. Backtracking, first to include P10, and then SQ3, yields a trial optimum of $588.78 × 10^3.

Iterations 4, 5, 6, and 7 result from further backtracking to evaluate other alternatives nominated for site 2. In each, we compute the bound and thus eliminate subsets of three plans after a single execution of the simulation-evaluation program.

TABLE 5. Summary of Iterations for Example

Iteration (1)	Measure for[a] Site 1 (2)	Measure for[a] Site 2 (3)	Measure for[a] Site 3 (4)	Total cost[b] (5)	Damage with plan[c] (6)	Net benefit or bound[b] (7)	Comment (8)
1a	R25	*HPM*	*HPM*	110.10	237.96	817.77	Subset bound
1b	R25	L83	*HPM*	130.87	325.09	709.87	Subset bound
1c	R25	L83	P20	299.69	400.94	465.20	Trial optimum
2	R25	L83	P10	248.31	418.67	498.85	New optimum
3	R25	L83	SQ3	130.87	446.19	588.78	New optimum
4	R25	SQ1	*HPM*	110.10	727.73	328.00	Eliminate subset
5	R25	D12	*HPM*	208.20	539.36	328.00	Eliminate subset
6	R25	D75	*HPM*	450.18	356.41	359.24	Eliminate subset
7	R25	L17	*HPM*	11SQ38	688.51	364.14	Eliminate subset
8	R68	*HPM*	*HPM*	514.24	65.85	585.74	Eliminate subset
9b	SQ1	*HPM*	*HPM*	0.00	525.55	640.28	Subset bound
9a	SQ1	SQ2	*HPM*	0.00	1,015.32	150.51	Eliminate plan
10	SQ1	D12	*HPM*	98.10	826.95	240.78	Eliminate subset
11	SQ1	D75	*HPM*	340.08	644.00	181.75	Eliminate subset
12	SQ1	L17	*HPM*	3.08	976.10	186.75	Eliminate subset
13	SQ1	L83	*HPM*	20.77	612.68	532.38	Eliminate subset

[a] *HPM* = the hypothetical perfect measure.

[b] Annual value, in $1,000.

[c] Expected annual value, in $1,000.

Iteration 8 results from backtracking to consider the subset of plans that includes R68. With the HEC-1 results, we compute the upper bound on net benefit of all plans that include R68. This bound, 585.74 thousand, is less than the trial optimum of iteration 3. Therefore, none of the plans that include R68 will yield net benefit greater than the benefit of the plan with R25, L83, and SQ3. We eliminate from further consideration all 15 plans that include R68. We should note that eliminating these plans leaves little margin for error in cost and benefit estimation. If the net benefit of iteration is 1% less, we would mistakenly eliminate plans here. To avoid this, we could use a tolerance in the comparisons. For example, unless the bound is at least 6% less than the trial optimum, we might chose to continue separating and evaluating subset that include R68.

Iterations 9, 10, 11, 12, and 13 complete the analysis. In each of these, we eliminate three plans via comparison of the subset bound with the trial optimum.

Our initial guess was fortuitous. However, regardless of the starting point or the selection rule used, the procedure always identifies the optimal combination of the alternatives proposed. A good heuristic strategy may define a good bound. This will speed elimination of inferior plans without detailed evaluation.

CONCLUSIONS

The branch-and-bound enumeration procedure improves the search for the optimal floodplain management plan. The procedure considers all combinations of user-specified measures, but eliminates from detailed evaluation combinations that clearly are non-optimal. HEC programs simulate system performance, evaluate damage reduction, and manage data.

The branch-and-bound enumeration procedure has, we believe, distinct advantages for plan formulation. The evaluation procedure is consistent with current plan formulation procedures. The floodplain-management expert (or perhaps, in the future, an expert system) nominates the alternatives. In doing so, the expert can incorporate technical, financial, social, environmental, and political objectives and constraints that may otherwise be difficult to model. The enumeration procedure only evaluates the alternatives efficiently.

The procedure can use any desired criteria for optimality and feasibility. For example, we could modify Eq. 1 to account for environmental objectives. Similarly, we can eliminate in the enumeration any combinations of measures that are politically infeasible, if we can identify the combinations or their characteristics beforehand.

Practitioners often criticize or avoid mathematical-programming models because of the simplifications made to yield a tractable formulation. The enumeration-with-simulation procedure minimizes the simplification required by using accepted simulation tools. We propose using HEC simulation and evaluation programs, but we realize that some analysts prefer other programs. They can use these within the framework of the branch-and-bound procedure.

Finally, we feel that the branch-and-bound enumeration procedure has the advantage of being understandable. Our experience confirms Woolsey's idea that "people would rather live with a problem they cannot solve than accept a solution they cannot understand" (Woolsey 1975). Simulation is well understood. The branch-and-bound procedure augments, rather than replaces, that approach.

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Our procedure is an extension of original work by Ball, Bialas, and Loucks; we admire their creativity. We appreciate the advice offered by Darryl Davis of HEC, the earlier efforts of Teresa Bowen, and the suggestions of an anonymous reviewer.

APPENDIX I. Conversion to SI Units

To convert	To	Multiply by
acre-ft	m^3	1.23×10^3
cfs	cms	0.0283

APPENDIX II. REFERENCES

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APPENDIX III. NOTATION

The following symbols are used in this paper:

B_I = intensification benefit;
B_{IR} = inundation-reduction benefit;
B_L = location benefit;
C = total cost of implementing and maintaining the plan;
$C(\cdot)$ = cost of measure at the specified site;
D_{exist} = existing-condition flood damage;
D_{plan} = flood damage with the plan in place;
$E[\cdot]$ = the average or expected annual value of the argument;
$E[D(\cdot)_{exist}]$ = expected annual existing-condition damage at the specified site;
$E[D(\cdot)_{plan}]$ = expected annual damage at the specified site with the plan in place; and
NB = net benefit.

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