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This paper describes a technique that has been developed and programmed into an existing Hydrologic Engineering Center (HEC) computer model (6) that provides an estimate of the "best" size of the individual components of a complex interrelated system of urban flood-control works while using techniques of analysis that are very near to the present state-of-the-art in the Corps of Engineers in hydrologic modeling, cost analysis, and economic damage-frequency analysis. "Best" is defined as the combination of component sizes that yield the maximum value of system net benefits while observing performance standard constraints, if they exist. This capability has been developed so that a system consisting of up to six detention storage reservoirs, two within or out of basin diversions, and two pumping facilities can be automatically sized.

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Optimal Sizing of Urban Flood-Control Systems[a]

By Darryl W. Davis,[1] M. ASCE

Introduction

Flood-control measures within urban areas frequently consist of detention storage reservoirs, channel modifications, land-use controls, levees, flood proofing, and pumping facilities. A range of alternative system configurations and component sizes can usually be identified that will accomplish a specific technical objective, such as a specified degree of protection. The need to determine the appropriate size of the components of the system has stimulated efforts to formalize the analysis of tradeoffs between facilities, performance, and costs. For example, there is a combination of best sizes for each component in a system that would maximize the system's net value or accomplish a performance standard most efficiently.

The problem of determining the best sizes of a number of interrelated components is not new and a large number of analytical optimization procedures have been developed (1,3,5,7,9). These techniques have been quite successful in areas where the objectives are well defined, and the system response to the interaction of system components can be modeled with fairly simple mathematical relationships. The application of these techniques to water resource systems has been mostly by research groups operating in the case study mode (analyzing others' problems) as contrasted with functioning as an integral part of planning studies. A major reason for this is that water resource systems are extremely complex and to define accurately the functioning of the system requires detailed analysis. In addition, there is considerable uncertainty in system inputs and desired outputs. Water resources planners have been reluctant to

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simplify their systems to the degree necessary to make use of the more automated optimization procedures. The belief among planners is that the simplifications result in not capturing the essence of the system performance and component interactions.

This paper describes a technique that has been developed and programmed into an existing Hydrologic Engineering Center (HEC) computer model (6) that provides an estimate of the "best" size of the individual components of a complex interrelated system of urban flood-control works while using techniques of analysis that are very near to the present state-of-the-art in the Corps of Engineers in hydrologic modeling, cost analysis, and economic damage-frequency analysis. "Best" is defined as the combination of component sizes that yield the maximum value of system net benefits while observing performance standard constraints, if they exist. This capability has been developed so that a system consisting of up to six detention storage reservoirs, two within or out of basin diversions, and two pumping facilities can be automatically sized.

The technique that has been developed is designed to be compatible with present urban flood-control plan formulation methodology. The objective in its development was the creation of the capability for performing the studies in the usual fashion but to remove the tedium of searching for the best component sizes for each system alternative and thus encourage the study of a wider range of system alternatives than might otherwise be considered. Within this framework, the technique will also permit study of the relative sensitivity of the system to changes in facility costs, project discount rates, flood-plain land-use controls, and hydrologic performance standards, so that an array of information can be easily developed that could be used in formulating a desired management plan.

Plan Formulation Methodology

The technique has been developed to be as compatible with current urban flood-control plan formulation methodology as possible. A brief conceptual review of the plan formulation and evaluation process in urban flood-control studies should assist in understanding the development of the technique and its probable role in planning studies.

Plan formulation begins when public meetings are held and investigations are initiated to determine the broad social objectives within the study area. The social objectives primarily serve to assist in defining: (1) The concerns of the public; (2) concepts to be used in structuring alternatives; and (3) technical objectives and criteria that will be used in structuring the technologic components of management alternatives. For example, such social objectives as alleviating a specific dangerous flooding situation, providing a regional recreation opportunity, removing the cause of stunted economic growth, and providing a better community environment would be translated into a range of management alternatives that would consider the location and severity of flooding, possibilities of joint site use for specific temporary detention storage and urban recreations, and appropriate performance standards for components of the systems. The technical analysis is then performed to define the performance of the alternative systems and assess their economic, social, and environmental assets and liabilities.

The information developed by these analyses is used in successive refinement of the alternatives and development of implementation strategies. An objective within the successive refinement of alternatives is usually to determine the system, which can include physical works and other nonstructural measures, that will in the aggregate perform their function most economically. The most economically efficient size for a system exists when the difference between the total annual benefits and the total annual cost is maximized, which is termed the scale of maximum net benefits. In studies with a few components, e.g., two or less, the usual approach is to nominate a few selected component sizes, determine their performance, and graphically estimate the particular component scales that would accomplish the economic objective. For more than two components, graphical analysis is virtually impossible.

The next step in formulation is usually to "select" a performance standard, giving appropriate weight to social and environmental objectives. The performance standard is usually expressed as the "degree of protection," which is the exceedence interval of the hydrologic event that can be controlled so that flood damages do not result. A 50-yr degree of protection would be provided by a system that reduced the stages at potential damage areas for a 50-yr exceedence interval flood to stages below damaging levels.

Another sizing problem exists upon having selected a performance standard: To determine the size of each system component that will accomplish the target degree of protection most efficiently and economically. The usual approach is to size the facilities so that they accomplish the target performance standard at the least overall annual cost. A better approach would be to size the facilities to satisfy the target performance standard while, to the extent possible, maximizing system net benefits. This concept recognizes that different components, such as reservoirs and levees, perform differently for events that exceed the magnitude of the performance target event.

The determination of the size of each component in a system that will maximize net benefits or accomplish the performance standard is by no means trivial when more than two major components can take on a range of sizes. For complex urban flood management systems, the analysis can be extremely tedious and consume a very large portion of the efforts and energies of those performing the studies, if they are done at all.

The issue of timing or sequencing of implementation of system components once the desirable components have been sized has been examined by James (8). Because of land-use projection uncertainties and questions pertaining to policies related to implicit consideration of future economic growth, the technique presented herein does not directly deal with the issue. Instead, as subsequently pointed out, it is suggested that the sensitivity of the solution to timing, particularly as represented by future development if timing is believed of significance, be determined by varying the assumed discounted damage relationships.

Optimization Technique

The strategy for developing the technique consisted of first devising a computer simulation model for simulating the hydrologic and economic performance of flood-control systems, then structuring an automatic search procedure that would exercise the simulation model by successively adjusting the scales of each component of the system until the solution is found.

When it is decided to automatically provide an estimate of the best size or the "best" anything in a mathematical sense, a certain number of requirements immediately become apparent. The first is that "best" must be precisely and uniquely defined by an indicator or index that integrates all of the desired performance characteristics of the system that is being analyzed. This index is normally termed the objective function. In addition, the capability to adjust automatically the size of each component within a feasible range and evaluate the resulting change in performance of the system must be devised. Then a search procedure that is as nearly foolproof as possible must be developed.

Objective Function.—The plan formulation strategy previously described included initially determining an economically optimum system (unconstrained maximum net benefits) as a starting point for determining a performance standard for subsequent analyses. The unconstrained economic optimum can be characterized by an index of the system performance (objective function) that consists of the sum of the total annual system cost and the total value of the system's expected annual flood damages. If we label this the total social cost of flooding, then the objective is to find the combination of component sizes of the system that results in the minimum total value of system social cost of flooding. Obviously, the system that results in minimum total social cost as previously defined is exactly the system that will result in the maximum value of system net benefits.

The second sizing phase in plan formulation was to determine the component sizes that would accomplish the performance standard (degree of protection) most efficiently and economically. The objective function that was adopted from among several that were tested for determining the system that will maximize system net benefits while satisfying performance standards, if they exist, is

$$Z = \left(\sum_{i=1}^{n} C_i + \sum_{j=1}^{k} \mathrm{AD}_j\right)\left[\sum_{j=1}^{k}\left(\frac{\mathrm{DEV}}{A\,Q_t}\right)_j^4 + \mathrm{CNST}\right] \quad \text{. . . . . (1)}$$

in which Z = system performance index (magnitude of objective function); C_i = equivalent annual cost of system component i; AD_j = expected annual damage at location j; n = number of system components to be optimized; k = number of damage locations (damage centers); DEV = $(Q_z - Q_t)$ if the result is positive, otherwise DEV = 0; Q_z = flow (stage) for target degree of protection at damage location j; Q_t = target flow (stage) for target degree of protection at damage location j; and A, CNST = normalizing constants and weights, usually 0.1 and 1.0, respectively. The function is comprised of two parts; the total annual social cost of flooding and a multiplier that penalizes the function whenever the operation of the components results in performance that is not within a certain tolerance of the desired system performance target. The penalty is merely a devise for forcing the performance target to be met. When the flow, Q_z, is equal to or less than the target flows, Q_t, for a given system, then for a constant, CNST, of 1.0 the value of the objective function is the sum of the total annual system cost and expected annual flood damage. The initial "unconstrained" sizing problem is therefore solved by setting CNST to 1.0 and Q_t to a very high value. Providing a value of 0.1 for the normalizing constant, A, in effect says that when performance Q_z is within 10% of the target, Q_t, the weight between the social cost of flooding and the hydrologic performance is equal. For deviations larger than 10% the components are penalized at the rate of the fourth power; for deviations less than 10% the penalty is reduced rapidly.

The objective function is a meaningful representation of system performance only if it is possible to accurately calculate and develop confidence in the individual components comprising the function. For example, the annual damage at a control point, AD_j, results from economic analyses that define potential damage and hydrologic analyses that define the exceedence frequency relationships. In order that this procedure be as nearly acceptable to Corps of Engineers users as possible, the hydrologic and economic analyses are performed by the computer simulation model by approximate current state-of-the-art methods in use by the Corps.

The hydrologic simulation is performed using rainfall-runoff procedures that consist of: (1) Subdividing the watershed into subbasins; (2) computation of

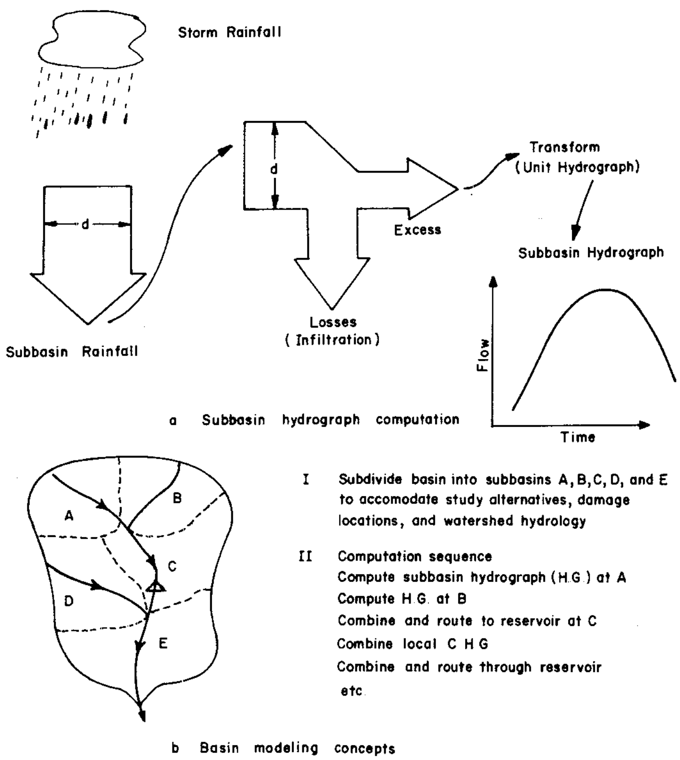

FIG. 1.—Rainfall-Runoff Computations for Complex Basin

subbasin average rainfall; (3) extraction of subbasin losses to yield rainfall excess; (4) computation of a runoff hydrograph from individual subbasins by use of the unit hydrograph procedure; (5) routing subbasin hydrographs to concentration points by application of hydrologic routing procedures; and (6) combining hydrographs at concentration points. The simulation is performed by the HEC-1 computer program (6) that has been in use by Corps hydrologists for a number of years. A schematic diagram of the computation of runoff hydrographs at various points in a complex basin is shown in Fig. 1.

The economic calculation of the expected value of annual damages is performed using the Corps procedure that consists of: (1) Estimating the economic consequence of a flood from a damage function that relates the damage for a flood event to the peak flow or stage; and (2) combining this function with the exceedence frequency relation of peak flow or stage to yield an exceedence frequency of damages relationship. This latter relationship is subsequently integrated to yield the expected value of annual damages. The simulation program accepts damage functions in the form of flow damage or stage damage relations, accepts exceedence frequency functions in the form of flow or stage exceedence frequency, and develops from hydrologic input a range of hydrologic runoff events for the watershed that are used to develop modified conditions (with

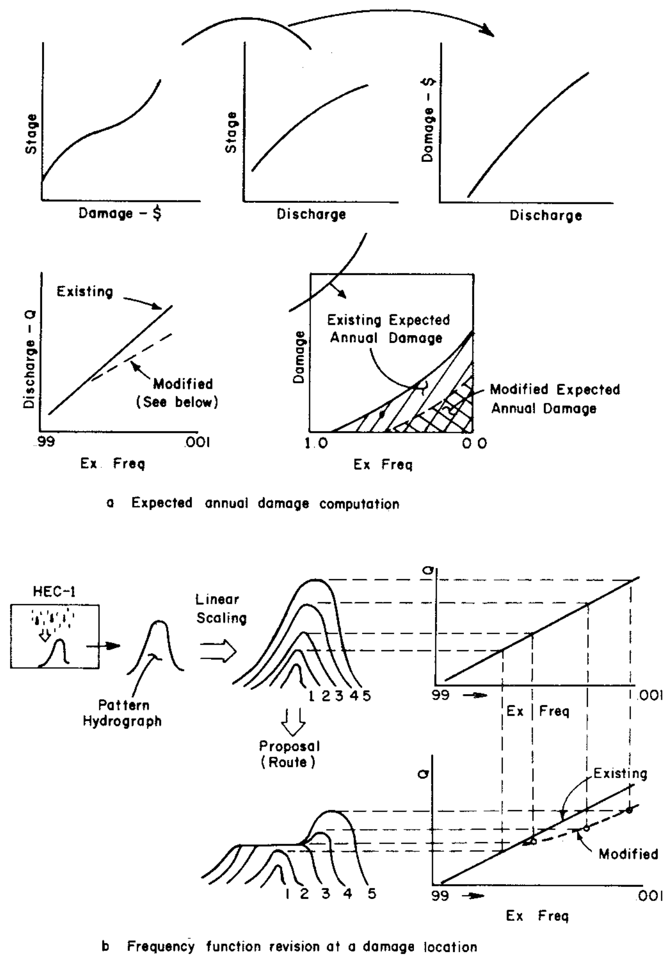

FIG. 2.—Concepts in Frequency-Flow-Damage Analysis

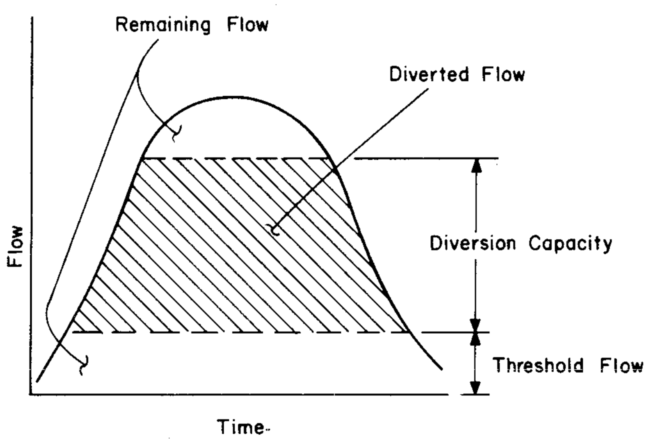

FIG. 3.—Effect of Diversion on Flood Hydrograph

the proposed system) exceedence frequency relationships at all damage centers. The expected value of annual damages is automatically computed within the simulation. Fig. 2 contains a diagram showing this procedure which is explained in detail in Addendum 3 of Ref. 1.

Flood-Control System Components

The components whose sizes may be automatically determined include detention storage reservoirs, pumping plants, and diversions. Fixed facilities, e.g., existing reservoirs, can be included without being considered components to be optimized.

Storage Reservoir Characterization.—The detention storage reservoirs that may be considered variable in size are those for which it is possible to define the operating characteristics as a unique function of the storage content within the reservoir. A reservoir with uncontrolled outlet works, such as an overflow spillway, exactly meets this requirement. To provide capability for automatic adjustment of operating characteristics, a reservoir is characterized by the following:

1. The outflow characteristics of a low level outlet, which is defined by the center line elevation of the outlet and an orifice equation of the form

$$Q = Ka(2g)^{1/2}(H)^{\exp} \quad (2)$$

in which K = orifice discharge coefficient; a = outlet flow area; H = head on low level outlet; and exp = exponent dependent on tailwater conditions, 0.5 if no tailwater.

2. The overflow characteristics of a spillway which is defined by a weir equation of the form

$$Q = K_* L H_*^{3/2} \quad (3)$$

in which K_* = weir discharge coefficient; L = length of spillway; and H_* = head on spillway.

3. The site storage characteristics which are defined by an elevation-storage capacity relationship.

For an index storage level to be optimized, which is the storage at the elevation of the spillway crest, the foregoing relationships are merged to define the reservoir's outflow as a function of the storage level in the reservoir (storage outflow function). The storage outflow function is subsequently used in the simulation to route flows through the reservoir by modified Puls procedure.

Two alternative optimization modes are possible for a reservoir. In the usual mode a reservoir that can be characterized by a low level outlet and an overflow weir as aforementioned will be automatically adjusted in its index storage capacity, along with all other system components, to achieve the minimum value of the objective function. The cost function for the reservoir in the usual mode consists of a capital cost function and an associated capital recovery factor for converting the capital cost to annual cost, and the annual cost of operation, maintenance, and replacement expressed as a proportion of the capital cost. The capital cost function land acquisition and construction costs, interest during construction, etc., expressed as a function of the index storage size of the reservoir. The capital cost for a specific size is interpolated from this function and the equivalent annual cost is computed as the product of the capital cost and the capital recovery factor for the appropriate discount rate. The annual cost of operation, maintenance, and replacement is the product of the annual cost proportion and the interpolated capital cost. The total annual cost of the reservoir is the sum of these two costs.

In initial test applications of the technique to the Blue Waters Ditch studies of the authorized East St. Louis and Vicinity Interior Flood Control Project, it became apparent that for one component the "reservoir size" that was to be determined was in actuality the lands that were to be acquired because the "reservoir" embankment was sufficiently high so as to essentially contain all floods. The embankment was in fact a large proposed highway fill. The flow out of the reservoir would therefore pass only through the low level outlet and thus the only variable to control the operation of the reservoir was the capacity of the low level outlet. For this particular situation, a reservoir's operating characteristics are specified uniquely by the outflow characteristics of the low level outlet and the item regarding the reservoir that is to be optimized is the "size" of the outlet. The reservoir performance is characterized as before except it simply has no spillway and the discharge coefficient for the low level outlet is held constant and the area of the outlet opening is varied. The cost characterizations include a capital cost of outlet works function, and the reservoir capital cost function which would be primarily the cost of acquiring the reservoir site for the ponding level equivalent to a specified exceedence probability, taken as the degree of protection in this case. This characterization will be necessary for studying systems for urban areas that are protected by major levees, as is typical in many local protection projects where pumping is necessary to remove flood waters and the amount of ponding near the pumping facility is a function of the size of the pumping facility.

Pumping Plant Characterization.—A pumping facility removes volume from the system at a rate equal to the pumping capacity. The performance characteristics of a pumping plant are defined by an initial threshold water level at which the pump is activated and the discharge capacity of the pumping facility. In this analysis, it is assumed that water pumped from the system does not later appear at other locations in the system. The cost of a pumping facility is computed from a capital cost function and an associated capital recovery factor for converting to equivalent annual cost, the annual operation, maintenance, and replacement cost that is a proportion of the capital cost, and the annual power cost. The power cost is adjusted if the volume to be pumped changes as the system components sizes are being optimized. It can be demonstrated that despite the pumping capacity, the power costs would not materially change if the volume to be pumped does not change. The annual power costs are therefore adjusted only for water that is removed from the system by diversions or other pumping facilities.

Diversion Characterization.—A flow diversion transfers flow between locations within or removes flow from the system. The performance characteristics are defined by a threshold flow and a diversion capacity. The concept of the diversion is indicated in Fig. 3 by showing the effect on a flood hydrograph. Flow diverted at one location may be returned to the system at any downstream location so that it is possible to characterize a facility that would bypass a portion of flood flows around a damage location. The cost of a diversion facility is characterized similar to a pumping plant by a capital cost function, a capital recovery factor, and annual operation, maintenance, and replacement factor.

Search Procedure

The strategy used herein for automatically adjusting the component sizes such that an objective function can be minimized is that described previously

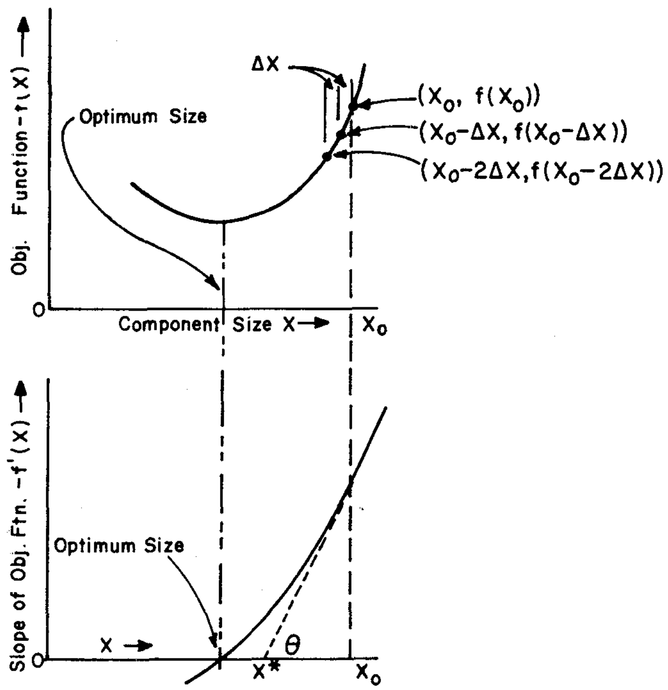

FIG. 4.—Adjustment of Component Size by Newton-Raphson Convergence Procedure

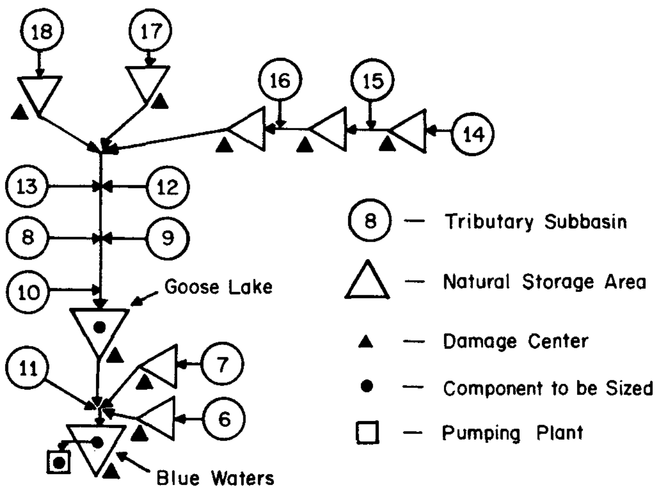

FIG. 5.—Schematic of Blue Waters Ditch System

by Beard (2). The procedure is the univariate gradient procedure that makes use of the trend characteristics of the objective function for selected small changes in the size of each component. The convergence procedure used to project the trend to determine improved component sizes is the Newton-Raphson convergence procedure. The optimization methodology proceeds as follows:

1. Trial sizes of all system components are nominated and the entire system is simulated in all of its hydrologic, cost, and economic detail to calculate the value of the objective function, which for unconstrained optimization is the sum of the equivalent annual cost and expected annual damage.
2. The size of one component is decreased by a small selected amount (1%) and the simulation is repeated for the entire system to compute a new value of the objective function. This is repeated again resulting in three unique values of the objective function for small changes in the size of one component.
3. From these three values, an estimate is made of the component size that would result in the minimum value of the objective function. The computation of the adjustment is shown in Fig. 4 and proceeds as follows:

$$f''\left(X_o - \frac{\Delta X}{2}\right) = \tan\theta = f'\left(X_o - \frac{\Delta X}{2}\right)\left[\left(X_o - \frac{\Delta X}{2}\right) - X^*\right]^{-1} \quad \text{. . . . . . (4)}$$

$$\text{or} \quad X^* = X_o - \left[f'\left(X_o - \frac{\Delta X}{2}\right)\right]\left[f''\left(X_o - \frac{\Delta X}{2}\right)\right]^{-1} - \frac{\Delta X}{2} \quad \text{. . . . . (5)}$$

$$\text{in which} \quad f'\left(X_o - \frac{\Delta X}{2}\right) = [f(X_o) - f(X_o - \Delta X)](\Delta X)^{-1} \quad \text{. . . . . (6)}$$

$$f''\left(X_o - \frac{\Delta X}{2}\right) = [f(X_o - 2\Delta X) - 2f(X_o - \Delta X) + f(X_o)](\Delta X)^{-2} \quad \text{. . . . . (7)}$$

and ΔX = incremental change in X; X = size of variable being optimized; X_o = present size of component X; and X^* = projected "new" size for X.
4. After adjustment of the size of the system component, the entire system is simulated again in detail to compute the new value of the objective function and, provided the objective function has decreased, the procedure then moves to the second system component whose scale is to be optimized.
5. The foregoing procedure is repeated for the second and all subsequent components to be optimized.
6. A single adjustment has now been made for each component for one complete search of the system component sizes. The procedure is then repeated for two more complete system searches.
7. The component whose change contributed the most to decreasing the objective function is adjusted next before another complete system search is performed.
8. The procedure is terminated when either no more improvement in the objective function can be made (within a tolerance) for the component making the greatest contribution to decreasing the objective function, or the complete search cycle is completed.

The efficiency of the search procedure and the degree of success in determining the optimum sizes for the components is a function of the behavior of the objective function and the starting values. If the objective function varies erratically with small adjustments in the component scales, chances of finding a unique optimum are less than with an objective function that varies regularly (termed well-behaved). Results of applications to date suggest that the objective function is reasonably well-behaved and that unique solutions do in fact come out of the procedure. However, note that this particular methodology (univariate gradient procedure) does not guarantee that the true optimum (global optimum) is achieved. However, the derived system will be very near optimum for the component sizes in the general order of magnitude of the initial component sizes. A study methodology that considers that local optimums may occur; e.g., testing a few starting values would be appropriate.

Application to Urban Flood-Control Project

The technique was developed for the United States Army Engineer District, St. Louis, Mo., for use in plan formulation studies for the Harding Ditch unit of the East St. Louis and Vicinity, Interior Flood Control Project. The District desired a technique that would enable automatically determining the scales of flood-control system components comprising three to four reservoirs, a diversion, and one to two pumping plants. The development work had proceeded well so that when it became necessary for the District to perform additional analysis of a unit of the project that had previously been studied, an application of the technique was undertaken to assist the studies and provide for testing. The area studied was the Blue Waters Ditch unit of the project that encompasses approx 9,000 acres of the American Bottoms area. The area consists of a number of smaller and a few major communities. A few drainage canals and levee segments exist and the lower (outlet) end of the area is protected by major levees of the Mississippi River system necessitating that most flood flows be pumped from the basin. Fig. 5 is a schematic of the system.

Previous studies had defined two detention storage sites and a pumping facility as potential system components. The technique was applied to determine the best size of the pumping facility and detention storage areas for a range of storage site characteristics, project discount rates, assumed economic conditions, and performance standards. A major objective of the study was to determine the sensitivity of the component scales to assumed flood-plain land-use controls. This was accomplished by optimizing the sizes of the components for: (1) No target degree of protection and economic flow-damage functions prepared for damage potential as it existed in 1973; (2) economic flow-damage functions reflecting uncontrolled future growth; and (3) for a reasonably controlled future growth compatible with the flood-control system. Optimization of the component sizes was then repeated for the same sets of data for a target degree of protection of 100-yr exceedence interval. The sensitivity of the system to detention site characteristics was examined by altering the reservoir elevation-storage and reservoir storage-cost functions and optimizing. The sensitivity to the project discount rate was examined by optimizing the component sizes for one of the previously studied conditions for three discount rates.

The results of the studies are preliminary and should be considered as a test application of the methodology rather than the final results of the formulation studies for Blue Waters. However, the studies were a real component of the plan formulation and evaluation strategy and the results presented in Table 1 are not a selected case study. The solutions were sufficiently promising that design will probably ensue based on the analysis performed. Table 1 presents a summary of results of selected optimization runs. An important revelation from this application was that it is possible to quantitatively determine a measure of the effect of a number of interesting system conditions, e.g., land-use controls. Also, the range of component sizes that are optimum under a variety of assumed conditions was limited in most instances so that considerable confidence was developed in system component sizes. The studies indicated a meaningful role for land-use controls as a component of an urban flood-control system and, to a limited extent, quantified its contribution and explicitly evaluated its role.

No additional development work is contemplated before the technique is applied to the Harding Ditch area. It should be possible in the Harding Ditch study

TABLE 1.—Summary of Selected Optimization Runs, Blue Waters Ditch, in thousands of dollars

System condition (1)	All pump, EF, PT = 100, 6-7/8% at 50, NS[a] (2)	EF, PT = 100, 6-7/8% at 50, NS (3)	EF, no PT, 6-7/8% at 50, NS (4)	EF, PT = 100, 6-7/8% at 50, MS (5)	EF, PT = 100, 3-1/4% at 100, NS (6)
System capital cost	24,600	16,880	13,229	24,800	17,000
Amortized capital cost	1,777	1,204	944	1,771	578
Operation, maintenance, power, and replacement cost	94	61	45	66	61
Total annual cost	1,870	1,265	988	1,838	639
Existing annual damages	1,085	1,085	1,085	1,085	1,085
Residual annual damages	25	49	106	23	50
Annual damage reduction	1,060	1,036	979	1,062	1,035
System net benefits	−811	−229	−9	−776	396
Optimum Goose Lake storage	200 acre-ft	800 acre-ft	1,800 acre-ft	600 acre-ft	800 acre-ft
Optimum Blue Waters storage	400 acre-ft	1,400 acre-ft	1,700 acre-ft	1,200 acre-ft	1,400 acre-ft
Optimum Pump capacity	7,000 cfs	2,600 cfs	1,100 cfs	3,300 cfs	2,600 cfs

[a] Pumping is emphasized by requiring all flow to be pumped that is in excess of the natural capability of existing system to provide 100-yr protection.

Note: EF = existing land use assumed for future; CF = controlled future land use; PT = exceedence interval performance target; NS = natural storage; MS = excavation in detention areas that modify the storage.

to further test the methodology as to its value in plan formulation and evaluation studies. If the results of the initial application in the Blue Waters Ditch plan formulation studies are an indication of its utility, it will have considerable value in studies where a range of alternative systems with a number of components are to be studied.

Information Requirements and Output Results

The technique has been designed to be consistent with plan formulation strategies in use by many Corps of Engineers offices that are studying urban flood control and major drainage projects. The methodology is in fact not limited to urban flood-control studies and is equally applicable to other flood-control studies for which the assumptions of the operating characteristics of storage reservoirs, pumping, and diversions apply. The information needed to apply the technique is essentially no different than the usual procedures used in Corps of Engineers flood-control plan formulation studies.

Data Requirements.—The level of data refinement needed to model the rainfall-runoff response of the basin, characterize the operation of system components, compute system costs, and perform economic damage computations can vary but should be at least feasibility level. The hydrologic data required are the size and topology of the subbasin subdivision of the basin, precipitation for each subbasin for a representative storm, unit hydrograph, loss rates, and base flow recession for each subbasin, streamflow routing criteria for each channel reach, and reservoir routing criteria for all reservoirs. Exceedence frequency relations for each damage center for existing conditions must be developed and provided.

The system cost functions require tabulation of capital costs for a range of facility sizes, the capital recovery factor for each facility, the annual operation, maintenance, and replacement costs, power costs, and costs of any fixed facilities (not considered variable) to be included. A range of capital recovery factors should be developed for use in assessing the sensitivity of the solution to discount rates and investment timing.

The economic functions required are flow-damage or stage-damage relationships for each damage center. The functions should reflect all economic consequences of a flood event and should be present worth for any assumed future change in flood-plain land use. A number of damage functions should be prepared representative of a range of assumed future conditions. The study of nonstructural measures requires manipulation of the damage functions, e.g., flood-proofing measures are reflected by displacing a portion of the damage function within the elevation range that flood proofing is considered.

As might be expected when a tool becomes available that provides expanded capability, there is the tendency to attempt to more precisely define the hydrologic and economic performance than would be done otherwise. For example, in the usual study procedure, two damage centers might be used as index points for a reach of stream whereas with the capability available herein twice that many damage centers might be used which would generate additional study. An even stronger urge seems to arise to answer more "what if" questions. While this is somewhat the objective of a technique like this one, the urge should be at least mildly resisted.

Development of general performance and cost functions for the system components requires additional analysis. In a study that is of necessity not considering a wide range of component sizes, a single or perhaps two detailed cost estimates might be developed. For the optimization methodology, cost functions that relate to component size are needed which requires a different philosophy of cost estimating. General cost functions are needed initially and the detailed cost estimates deferred until approximate component scales have been determined by the studies. The generalized reservoir performance characteristics require additional hydraulic analysis to develop preliminary sizes for outlet works and spillways.

Output Results.—The information output from the application of this technique could, if not carefully controlled by a pragmatic study procedure, engulf the analyst. The technique provides the capability to "what if" a great number of items that probably would not be otherwise analyzed. Tools of this kind should of course be applied to conduct sensitivity analysis but within reason so that only information useful in the planning study is generated. It is worth emphasizing herein that all analysis tools, and in particular computerized methodology, have as their primary function the generation of information that will be of use in decision making; not removing any decision-making requirements from the planning function. Data are not necessarily information.

The outputs of a system optimization run for a set of system components, performance functions costs, and economic functions are: (1) The derived optimal size of each component of the system; (2) complete hydrologic simulation for the derived system; (3) economic expected annual damage analysis for each damage center in the system; (4) costs for each component of the system; and (5) a system summary of component sizes, cost, performance, and system net benefits for the derived optimum system. Ref. 4 contains detailed illustrated examples of data coding and program output together with explanations of data sources and output interpretation.

Resources and Costs.—The Blue Waters Ditch analysis provides some insight into the manpower requirements and computer costs of applying this technique. The information had been previously developed for the Blue Waters Ditch area. The primary effort was therefore to assemble the hydrologic data of loss rates, unit hydrographs, routing criteria, etc., economic flow damage information for the damage centers, and cost relationships in a form acceptable to the computer program. The specific studies were processed and information analyzed as the results became available. There were nine damage centers within the basin; nine storage areas, two of which were variable in size; and one pumping facility. The data preparation for the processing required about a man-week on the part of a hydrologist, economist, and water resources planner. The detail processing and interaction for the studies required about another week's time of each of these individuals. The computer time associated with processing a run was not trivial. Efficient processing for a complex system such as Blue Waters requires a large capacity high-speed computer. While computer execution times are rather meaningless because they are unique to a specific computer facility and optimization problem, the following computer resources used for the Blue Waters studies might be of interest. To process a given system configuration to determine the optimum size of each of three components optimized and to output the results required 15 min of accounting unit equivalents on a CDC 7600 computer and resulted in costs that ranged between $30 and $50 per computer run. The actual execution time ranged between 1.5 min and 2.0 min but a great amount of input-output and system storage were required. The study results were generated by about 12–15 successful computer runs.

Summary and Conclusions

A technique has been developed and the capability added to an existing Corps of Engineers computer program, HEC-1 (1), that automatically determines the sizes of urban flood-control system components that result in maximizing total

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system net benefits subject to accomplishment of performance targets. The system is described by hydrologic data, component performance, and cost functions and flow damage information for damage centers. The system components that may be sized include detention storage reservoirs, pumping, and diversion facilities. Initial applications suggest that the technique has considerable value in urban flood-control plan formulation and evaluation studies.

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Appendix II.—Notation

The following symbols are used in this paper:

A = normalizing constant;
AD_j = location expected annual damage;
a = outlet flow area;
C_i = component equivalent annual cost;
CNST = weighting constant;
DEV = difference between target and simulated flow;
EXP = exponent for tailwater conditions;
$f(X)$ = magnitude of objective function;

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$f'(X)$	=	numerical first derivative of $f(X)$;
$f''(X)$	=	numerical second derivative of $f(X)$;
H	=	head on low level outlet;
H_*	=	head on spillway;
K	=	orifice discharge coefficient;
K_*	=	weir discharge coefficient;
k	=	number of damage locations;
L	=	length of spillway;
n	=	number of system components optimized;
Q	=	flow rate;
Q_t	=	target flow for target degree of protection;
Q_z	=	flow (stage) for target degree of protection;
X	=	size of variable being optimized;
Z	=	system performance index; and
ΔX	=	incremental change in X.

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