US Army Corps
of Engineers
Hydrologic Engineering Center

Dredged-Material Disposal System Capacity Expansion

April 1986

TP-107

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
April 1986	Technical Paper	

4. TITLE AND SUBTITLE Dredged-Material Disposal System Capacity Expansion	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) David T. Ford	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5F. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center (HEC) 609 Second Street Davis, CA 95616-4687	**8. PERFORMING ORGANIZATION REPORT NUMBER** TP-107
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/ MONITOR'S ACRONYM(S)**
	11. SPONSOR/ MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

This is Paper No. 20565, published in Vol. 112, No. 2 of the ASCE Journal of Hydraulic Engineering, April 1986

14. ABSTRACT

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15. SUBJECT TERMS

dredged-material management, planning, systems engineering, benefit-cost analysis, capacity expansion, branch-and-bound enumeration, geographic information systems

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
U	U	U	UU	24	**19b. TELEPHONE NUMBER**

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

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Dredged-Material Disposal System Capacity Expansion

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Abstract: An ensemble of analytical tools is used to identify capacity expansion alternatives for the Delaware River dredged-material disposal system. Characteristics of the river and riparian area are stored and analyzed with a geographic information system. Site attractiveness maps produced with these data yield an array of potential expansion sites. The least-costly schedule for acquisition of these sites is identified with branch-and-bound enumeration. For the enumeration, the operation cost of alternative expansion plans is evaluated with a network-flow programming model of the disposal system.

Delaware River Navigation System

The Delaware River navigation system, shown in Fig. 1, extends approximately 130 miles (209 km) from naturally deep water in the Delaware Bay to the port of Trenton, NJ. The system consists of 15 developed port areas and two open-bay ports. One-hundred-thirty-two million short tons (1.2×10^{12} N) of waterborne commerce are moved annually through these ports. To maintain the congressionally-authorized channel depth of 40 ft (12.2 m) required for this navigation, approximately 11,500,000 cu yd (8.8×10^6 m^3) of material are dredged annually from the Delaware River and tributary channels. The dredged material is disposed in 21 upland sites. These upland disposal sites are natural or man-made diked areas into which dredged material, in slurry form, is placed. In the containment sites, excess water drains and evaporates from the slurry, leaving solids. The volume is reduced 30 to 50%, depending on material characteristics and site-management practices. Most man-made disposal sites are filled to a depth of approximately 15 ft (4.6 m); the depth of natural sites depends on the topography.

In 1978, the staff of the Philadelphia District, US Army Corps of Engineers (USACE), conducted a study of the dredging system (USACE, 1979). The staff concluded from a simple mass analysis with forecasted annual dredging volumes that existing sites will be filled by 1990. Consequently, to maintain the waterborne commerce, additional capacity must be made available for disposal of the dredged material. The study report suggests alternative methods to produce this capacity, including improvement of operation to extend the useful lives of existing sites, more efficient allocation system-wide of the available capacity, and development of new disposal sites. To investigate these alternatives, an ensemble of analytical tools is used which includes a network-flow programming model of disposal system operation, a geographic information system

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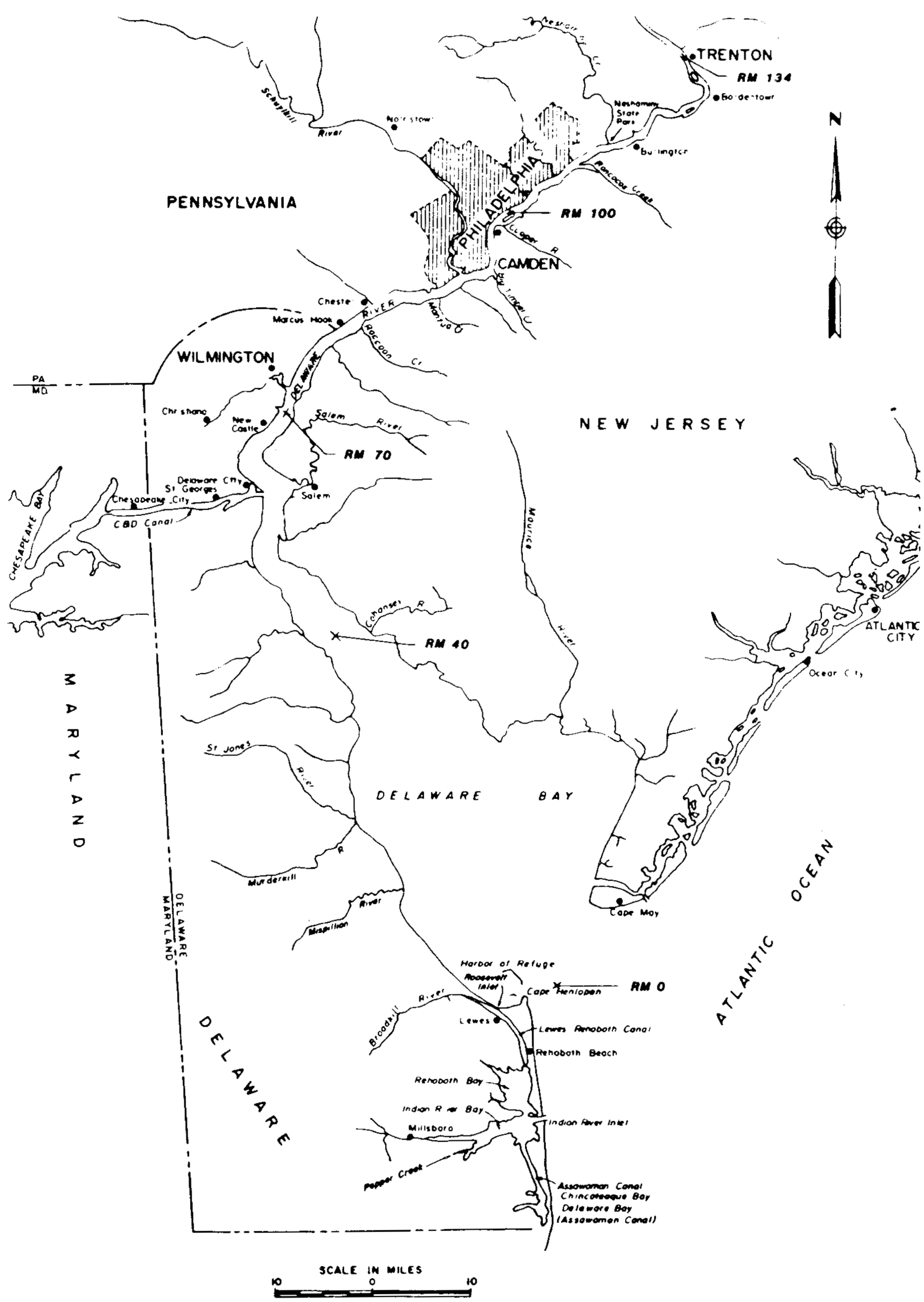


FIG. 1.—Delaware River Navigation System (USACE, 1984)

with associated attractiveness-mapping software, and a capacity-expansion model.

Analysis of System Operation

Analyzing the operation of an existing dredged-material disposal system was addressed early in the study, and a mathematical programming model was developed to determine the minimum cost and the associated operation policy for any system. This model is described in detail by Ford (1984). The model represents a disposal system as a network, as

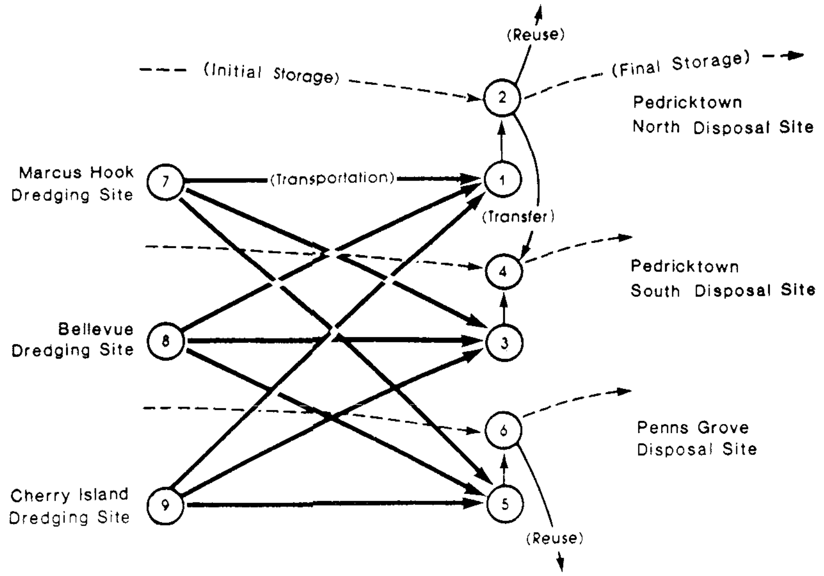


FIG. 2.—Network Representation of Disposal System

illustrated by Fig. 2. Dredging sites and disposal sites are represented by nodes. In Fig. 2, nodes 1–6 represent three disposal sites, and nodes 7–9 represent three dredging sites. The nodes are connected with arcs which represent transportation links through which material may be moved. The amount of material that can be moved is constrained by the capacity of the physical link; for example, an arc that represents a pipeline has a limitation on flow in the arc which is equal to the capacity of the pipeline. Also associated with each arc is a unit cost for moving material in that link in the disposal system. To analyze the operation of the system for multiple periods, a network is formed for each period, and these single-period networks are linked by arcs that represent storage of material in the disposal sites. A network-flow programming optimization algorithm is used to determine the minimum-cost assignment of material to the network arcs. The operation represented by this assignment is the optimal policy.

New Disposal Site Identification

Potential new disposal sites within the Delaware River system were identified by: (1) Selecting and collecting pertinent data for quantifying site suitability; (2) developing a computerized data base to manage the data; and (3) iteratively soliciting public expression of operation goals and constraints, computing and mapping indices of site attractiveness, and analyzing the maps in light of demands on the system.

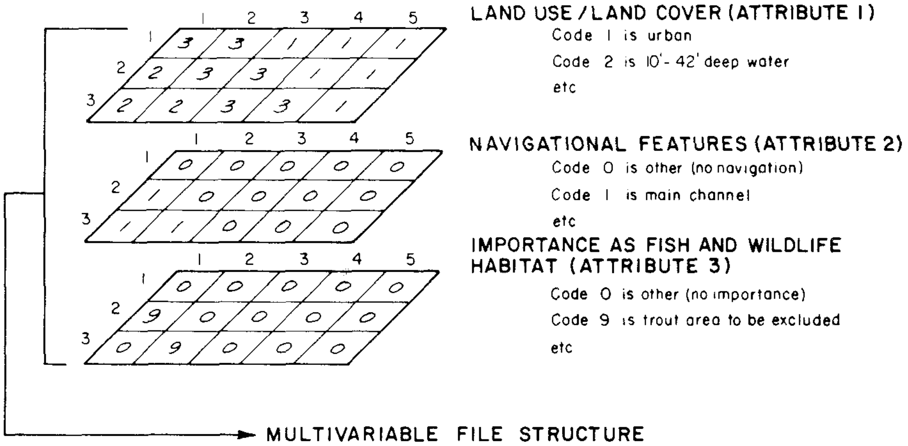
Physical, economic, environmental, social, and political criteria must be applied to determine the suitability of an area for development as a dredged-material disposal site. To aid the Corps planning team in defining these criteria as they apply to development in the Delaware River basin, an advisory committee representing the port community and Federal, state, and local agencies was formed. With the assistance of this committee, the planning team identified Delaware River and riparian-area attributes that have significant impact on selection of potential dis-

TABLE 1.—Attributes Included in GIS

Attribute (1)	Weight for map of Fig. 4 (2)
Land use/land cover	1.00
Navigational feature	1.00
Importance as fish and wildlife habitat	1.00
Archaelogical sensitivity	1.00
Historical significance	1.00
Location in groundwater recharge zone	1.00
Existing development	3.00
Recreational features	1.00
Location in groundwater protection zone	3.00
Elevation	3.00
Distance to navigation channel	5.00
Utilization as farmland	1.00
Wetland significance	1.00

posal sites. These attributes are listed in Col. 1 of Table 1. Due to the varied special interests of the members of the committee, the list of attributes is lengthy and broad-in-scope. However, the common factor of the attributes identified is that they are spatially-oriented.

Data Management.—Spatially-oriented data can be stored and analyzed conveniently with a geographic information system (GIS). The GIS selected for this study uses a grid-cell system (USACE, 1978a). With such a system, a regular, rectangular grid is superimposed on the study area, and the critical attributes are represented for each grid cell. Any number of attributes can be represented, as illustrated in Fig. 3.



ROW (1)	COLUMN (2)	ATTRIBUTE 1 (3)	ATTRIBUTE 2 (4)	ATTRIBUTE 3 (5)
1	1	3	0	0
1	2	3	0	0
1	3	1	0	0
⋮	⋮	⋮	⋮	⋮
2	1	2	1	9
2	2	3	0	0
etc				

FIG. 3.—Multiple-Variable Grid-Cell Data Bank

The grid-cell data base developed for the Delaware River system encompasses approximately 1,200 sq miles (3,108 km^2) including the river and a 5-mile (8-km) band on either side of the river. An 800 ft by 1,000 ft (244 m by 305 m) grid-cell size was selected, so the entire data bank includes approximately 43,500 cells. For each attribute, discrete categories are defined and assigned identifying codes, and the appropriate codes are stored. For example, the predominant navigational feature of each cell is classified as main channel (encoded as 1), entrance channel (encoded as 2), anchorage (encoded as 3), in-water disposal site (encoded as 4), or other (encoded as 0). Efficient techniques for classifying, encoding, and storing the data are described by USACE (1978b).

Attractiveness Mapping.—Potential new disposal sites are identified by overlaying geographic data, using an analytical procedure analogous to the map-coloring and overlaying procedure suggested by McHarg (1969). The analytical procedure, referred to as site-attractiveness mapping, develops an index value for each grid cell that represents the relative attractiveness of that cell for the desired activity, based on a weighted combination of pertinent geographic information. For display, the index value for each cell is represented by a combination of overprinted characters, and an attractiveness map is produced. Fig. 4 is an example of such an attractiveness map. In that map, the most-attractive cells are printed darkest, and less attractive cells are blank. Cells that must be

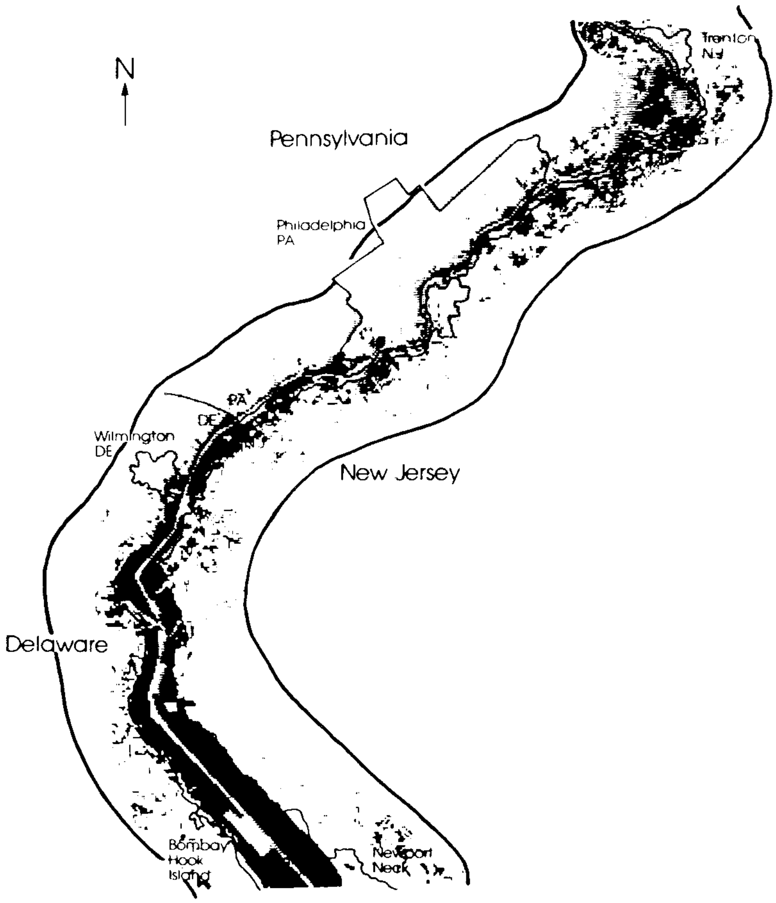


FIG. 4.—Attractiveness Map with Weights Emphasizing Economic Criteria (USACE, 1984)

excluded from consideration as expansion sites are printed lightest.

The attractiveness index for each grid cell of the data bank is computed as

$$INDEX(I,J) = \sum_{K=1}^{NATB} WT(K) * F_K[ATB(I,J,K)] \quad (1)$$

in which $INDEX(I,J)$ = attractiveness index of grid cell in row I, column J; K = index of attributes; $NATB$ = total number of attributes stored for each grid cell; $WT(K)$ = weight assigned for attribute K in the ranking of attributes (may be zero if attribute is not considered); $ATB(I,J,K)$ = coded value of attribute K for grid cell in row I, column J; and $F_K(\ )$ = a transformation function for attribute K. This transformation function converts the assigned code for values of attribute K to a numerical score between 0 and 10. If certain attribute values should preclude consideration of an area as a disposal site, a negative score is assigned, and the cell is excluded. No character is printed for that cell on the attractiveness maps. For example, when identifying new disposal sites with emphasis on economic criteria, the transformation function shown in Table 2 was selected for the navigation features: The negative values indicate that any cell that represents area in the main channel, in an entrance channel, or in an anchorage is not considered for development as a disposal site. Grid cells representing existing in-water disposal sites or those which fall into the "other" category are assigned a score of 10. This score is weighted and added to other scores for that cell to produce a weighted score.

Public Involvement.—Public expression of system operation goals and constraints on site location was solicited and compromise solutions were developed in a series of meetings with the advisory committee. In these meetings, the transformation functions and weights used to define the attractiveness index were varied according to the goals of the various interest groups, and the attractiveness model was executed to produce maps indicating potential new disposal sites in the study area. For example, Fig. 4 shows the relative attractiveness for developing new disposal sites from an economic point of view. The weights assigned in this case are shown in Col. 2 of Table 1.

The additional capacity available with new sites identified from various points of view is estimated by simple techniques and compared with the forecasted additional capacity required to maintain waterborne commerce at the desired level. Through this process, the shortfall, if any, associated with constraints imposed by each interest group may be

TABLE 2.—Navigation Feature Transformation Function

Feature (1)	Code (2)	Function value (3)
Main channel	1	−1
Entrance channel	2	−1
Anchorage	3	−1
In-water disposal	4	10
Other	0	10

quantified. Iterative application of the model, coupled with field investigation and engineering analysis eventually led to identification of a set of potential new sites which represent a compromise of goals and constraints on development.

Least Costly Expansion Plan Selection

Applying the site-attractiveness model to the GIS allows new sites which satisfy forecasted disposal needs to be identified. However, the analysis performed does not address site-acquisition scheduling. To address that problem, a capacity-expansion model was developed. This model systematically searches the set of alternative acquisition plans, evaluates the total cost of each, and identifies the optimal plan by comparing the alternatives.

Optimality Criteria.—The optimal capacity-expansion plan is defined here as the plan which satisfies all present and forecasted material-disposal requirements with minimum total cost. The total cost is the sum of the present value of: (1) The cost of new-site acquisition; (2) the cost that is a function of the allocation of dredged material to the available disposal sites (variable operation cost); and (3) the fixed cost of operating, maintaining, and repairing the disposal system (OMR cost).

Alternative Capacity-Expansion Models Considered.—The problem of determining the least-costly capacity-expansion plan for engineering systems has been solved with a cornucopia of systems analysis tools. Akileswaran, Morin, and Meier (1979) list 89 references to journal articles, reports, theses, and books in which the problem is analyzed and solutions are proposed. These solutions include applying heuristic decision rules, dynamic programming, integer programming, and enumeration techniques.

Heuristic decision rules are "seat-of-the-pants" methods for determining near-optimal solutions to well-defined optimization problems. With heuristic rules, any technique can be used for evaluating total cost of a capacity-expansion scheme. Bickel (1978) cites several such rules for capacity expansion, and Akileswaran, et al. (1979) examine the applicability of the heuristic approaches, list reasons for employing such approaches, and describe a number of heuristic rules for solving capacity-expansion problems.

Butcher, et al. (1969), Kuiper and Ortolano (1973), Morin (1975), and the Texas Water Development Board (1975) propose dynamic programming (DP) formulations which disaggregate the capacity expansion problem into a set of linked stages at which decisions must be made. At each stage, all possible expansion alternatives are evaluated explicitly. A state vector represents the status of each capacity expansion site at each stage. For the Delaware River system, four or five expansion sites typically are considered, with each site available in any of 50 years of operation. A DP formulation, in this case, will include 50 stages, and the state vector will include four or five state variables at each stage. Solution of a DP problem with a state vector of this dimension is difficult, at best.

Most integer programming (IP) formulations of the capacity expansion problem include a binary (0–1) decision variable for each potential site for each period during which that site can be acquired. For the optimal period of acquisition, this variable equals one, and it equals zero otherwise. Thus the contribution of a site to the total cost of a plan is the product of the acquisition cost and the binary variable. O'Laoghaire and Himmelblau (1972) propose such an IP formulation, and a similar formulation is used in the Texas Department of Water Resources program, CAPEX (1970). To represent a typical 50-yr analysis with four or five expansion sites for the Delaware River system, an IP formulation requires 200 to 250 binary decision variables. The computational requirements of a problem of this scale are reasonable. However, due to the interaction of the disposal sites, the total cost of an expansion plan for the Delaware River system is not a simple sum of site acquisition costs. Instead, the operation cost must be determined with each expansion plan and included as a component of the total cost. This computation necessitates use of a mixed integer programming (MIP) formulation that includes the binary decision variables plus all decision variables of a system operation model. Efficient solution of such a large-scale MIP problem is possible with only the most sophisticated computer hardware and software, and then only at great expense.

Branch-and-bound enumeration is a subset of IP that employs a structured, formalized procedure to search systematically for the optimal capacity-expansion plan. In the extreme, the technique enumerates all expansion schemes. The goal, however, is to eliminate sets of inferior expansion plans using bounds determined from a limited enumeration. The general properties of branch-and-bound techniques are described by Garfinkel and Nemhauser (1972), Lawler and Wood (1966), and Mitten (1970). Marks and Liebman (1970), Brill and Nakamura (1978), Nakamura and Brill (1979), Ball, Bialas, and Loucks (1978), Efroymson and Ray (1966), and Morin (1970) propose branch-and-bound methods for selection of the optimal combination of discrete capacity-expansion alternatives.

The procedure selected for capacity expansion of the Delaware River system employs a branch-and-bound algorithm with embedded heuristic rules, as suggested by Bickel (1978) and by Lesso, et al. (1975). This procedure was selected because: (1) It could be implemented within the budgetary and time constraints of the study; (2) it can be implemented with available computer hardware (Harris 500 minicomputer); (3) it does not require use of proprietary software; (4) it guarantees identification of the optimal solution regardless of the efficacy of the heuristic rule used; (5) it simplifies "changing of horses in the middle of the stream" as experience is gained in solving the expansion problem and better heuristic rules are discovered; and (6) most important, it permits direct application of the previously-developed network model for evaluation of variable operation cost.

Branch-and-Bound Procedure.—The branch-and-bound procedure identifies the least-costly dredged-material disposal system capacity-expansion plan by dividing the universe of alternative expansion plans into successively smaller, mutually-exclusive subsets (separating), choosing one of the subsets for further consideration (branching), estimating the minimum cost possible for the plans included in the subset (bounding), and comparing this cost with the cost of the best plan identified thus

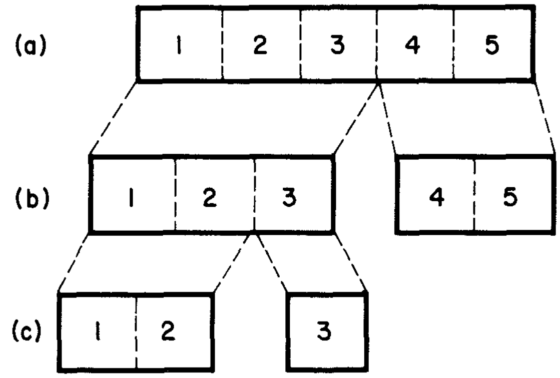


FIG. 5.—Subdivision of Expansion Plans

far. Inferior subsets are eliminated in the comparison. Non-inferior subsets are further divided, and the process continues until all plans are evaluated explicitly or eliminated by implicit comparison.

Fig. 5 illustrates conceptually how the branch-and-bound procedure separates, branches, compares, and eliminates alternatives in the search for the least-costly expansion plan. In this example, a single expansion site can be added to a system at the beginning of any of five periods. Thus, five alternative plans exist, as shown in Fig. 5(*a*). With the branch-and-bound procedure, a period is selected for separation of the plans into two mutually-exclusive subsets. The period is selected with a heuristic rule. Any rule can be used, for as Lesso, et al. (1975) point out, the ability of the branch-and-bound procedure to identify the optimal solution is not altered by the efficacy of the rules selected. The rules effect only the speed of solution. As shown in Fig. 5(*b*), the plans are separated at period 4. One subset includes plans in which the site is acquired between periods 1 and 3; the other subset includes plans in which the site is acquired between periods 4 and 5. The first subset is selected with a heuristic rule for further consideration, and the analysis branches to that subset. A lower bound on cost is estimated for the plans in that subset. This bound is computed in such a manner that it is guaranteed to be less than or equal the true cost of any plan in the subset.

As illustrated by Fig. 5(*c*), the procedure continues in the same fashion to separate further the subset with acquisition between periods 1 and 3. The separation is made at period 3, yielding two mutually-exclusive subsets: plans for acquisition between periods 1 and 2, and a plan for acquisition in period 3. The latter is selected and a lower bound is estimated for this subset. In the case of a subset that includes only one plan, this bound is, in fact, the true cost of expansion. For the example, this is the current minimum-cost plan, so it is defined as a trial optimal solution. The trial optimum is used subsequently for eliminating inferior plans.

When a subset cannot be separated further, or if a subset is eliminated through comparison with the trial optimum, the procedure is to backtrack to the most recently defined, but not yet evaluated, subset. If no such subset exists, the enumeration is complete, and the trial optimum is the solution. In Fig. 5, backtracking from the period 3 acquisition plan leads to the subset which includes acquisition in period 1 or 2. The lower bound on cost of these plans is evaluated. If this lower bound exceeds the trial optimum cost, both plans must be inferior to the trial optimum. This is so, and the subset is eliminated. Backtracking now leads to the subset including acquisition in period 4 or 5. The lower bound is estimated, the comparison is made, and, if necessary, the procedure continues as before.

Heuristic Separating and Branching Rules.—For the dredged-material disposal system application, the subsets of capacity-expansion plans are divided using heuristic rules that focus on the cost reduction possible if acquisition is delayed or accelerated. The rules identify a time period and, if multiple expansion sites are proposed, an expansion site which will serve as the basis for the separation.

For each expansion site J in a subset of plans, the unused volume per unit cost, $VC(J)$, is computed as follows:

$$VC(J) = \sum_{T=IPERA(J)}^{IPERB(J)} \frac{SMAX(J) - S(J,T)}{ACQCST(J) * PWF(R, T - IPER1)} \quad \text{(2)}$$

in which $IPERA(J)$ = earliest period for acquisition of site J for any plan in the subset; $IPERB(J)$ = last period for acquisition of site J for any plan in the subset; $SMAX(J)$ = capacity of disposal site J; $S(J,T)$ = volume of material stored in site J at end of period T, as determined by the network model of system operation; $ACQCST(J)$ = acquisition cost of site J; $PWF(R, T - IPER1)$ = present-worth factor, by which a cost at period T is converted with interest rate R to equivalent cost at period $IPER1$; and $IPER1$ = base period of analysis. The site with the maximum value of $VC(J)$ is selected as the basis for dividing the subset of plans. A low-cost site that is used extensively has a larger value of $VC(J)$, as does a high-cost site that is used little. In the first case, accelerating site acquisition is likely to reduce system cost, so the subset of plans is divided for that site, and earlier plans are considered. In the second case, postponing the acquisition is likely to reduce system cost, so the subset of plans is subdivided for that site, and later acquisition plans are considered.

Bounding.—A lower bound on total cost of plans in a subset is estimated by formulating a network model in which the fixed acquisition, and OMR costs plus operating costs are approximated as unit operating costs. These unit costs are assigned to the arcs which represent storage in the expansion site. Solution of the resulting network-flow-programming problem yields a cost for each period that is a fraction of the true acquisition and OMR costs. If the expansion site is filled in a period, the fraction is one, and the cost for the period is the actual acquisition, OMR, and operation cost. Otherwise, the fraction is less than one, and the cost in that period is less than the true cost. Furthermore, Lesso, et al. (1975) prove that the lower bound thus estimated for plans in a subset always equals or exceeds the true cost of the individual plans in the subset. Thus in the example from Fig. 5, the bound on the set which includes plans with expansion in period 1, 2, or 3 equals or exceeds the bound on the set of all five plans. Furthermore, the lower bound of the subset which includes acquisition in period 3 exceeds all of these.

Eliminating Subsets.—The important result of the characteristics of the lower bound estimate is that an entire subset may be eliminated if the lower bound exceeds the cost of a known feasible solution. The branch-and-bound procedure thus is able to eliminate, without explicit evaluation, subsets of plans that are clearly inferior. For example, in Fig. 5, if the lower bound of the subset that includes acquisition in period 1 or 2 exceeds the cost of acquisition in period 3, all the plans in that subset can be eliminated. The cost of expansion in period 1 or of expansion in period 2 exceeds the lower bound of the 1–2 subset, so these plans have been evaluated implicitly and can be eliminated from further consideration.

Example Application.—Fig. 6 illustrates a subsystem of the Delaware River system to which the branch-and-bound algorithm is applied to identify the least-costly capacity-expansion plan. The subsystem includes two dredging sites, two existing disposal sites, and three disposal sites which will be added to the system in the year 2000. The Wilmington Harbor South site may be acquired in any year between 1981 and 2000, if such acquisition is economically justified. Annual operation for 1981 to 2030 is analyzed. (Any other time step could be selected if data are available.)

Fig. 7 is a reproduction of a portion of the output from a computer program which implements the branch-and-bound algorithm and the network-flow programming model of the disposal system operation (USACE, 1984). The earliest and latest periods of the plans in each subset are shown for each iteration in the columns beneath the heading SITE ACQ. PERIOD. The cost shown in the column headed TOTAL NET COST is the cost computed with the network model using the unit-cost approximation of acquisition cost.

In iteration 1, a lower bound is estimated for the set of expansions plans in which the Wilmington Harbor South site is acquired between 1981 and 2000. This is accomplished by formulating a network model in which the site is included in the system, with unit cost approximations of the acquisition and OMR cost assigned to the arcs. The network model has approximately 700 nodes and 1,200 arcs. The conclusion from so-

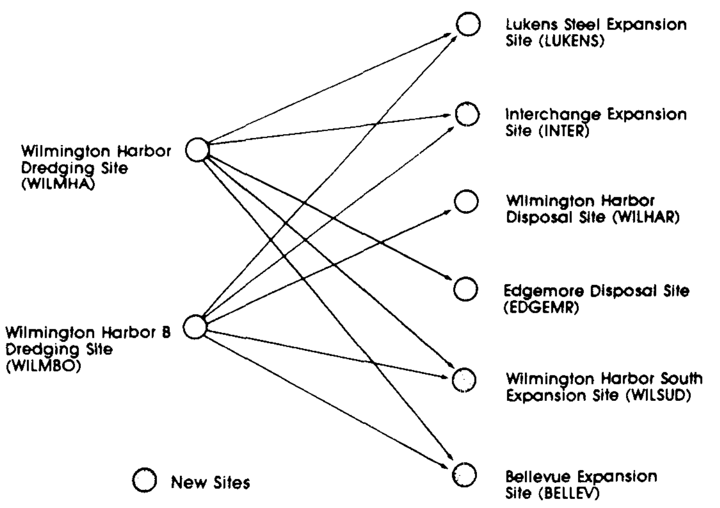


FIG. 6.—System for Capacity Expansion Example

CAPACITY EXPANSION ITERATION LOG

ITER	SITE ID	SITE ACQ. PERIOD		LEASE TERM. PER.	SITE TERM. PER.	PRESENT VALUE ACQ.+RENEG.+OMR COST	PRESENT VALUE OPERATION COST	TOTAL NET COST	
0	WILSUD	1981	2031	2031	2031	****************	****************	23159250.	APPROXIMATION
1	WILSUD	1981	2000	2031	2031	****************	****************	23364387.	APPROXIMATION
2	WILSUD	1997	2000	2031	2031	****************	****************	****************	INFEASIBLE
3	WILSUD	1981	1996	2031	2031	****************	****************	23500275.	APPROXIMATION
4	WILSUD	1990	1996	2031	2031	****************	****************	23515395.	APPROXIMATION
5	WILSUD	1994	1996	2031	2031	****************	****************	****************	INFEASIBLE
6	WILSUD	1990	1993	2031	2031	****************	****************	23661624.	APPROXIMATION
7	WILSUD	1992	1993	2031	2031	****************	****************	****************	INFEASIBLE
8	WILSUD	1990	1991	2031	2031	****************	****************	23786639.	APPROXIMATION
9	WILSUD	1991	1991	2031	2031	****************	****************	****************	INFEASIBLE
10	WILSUD	1990	1990	2031	2031	****************	****************	23786139.	
11	WILSUD	1981	1989	2031	2031	****************	****************	23909040.	APPROXIMATION
12	WILSUD	2031	2031	2031	2031	****************	****************	****************	INFEASIBLE

FIG. 7.—Program Output

lution of the network is that acquiring the site between 1981 and 2000 and operating it until 2030 will cost at least $23,364,387.

For iteration 2, the set of plans is separated into two mutually-exclusive subsets, using the heuristic rule to determine how the division is to be made. In this case, the first subset includes all capacity-expansion plans in which the site is acquired between 1981 and 1996, inclusive, and the second subset includes all plans in which the site is acquired between 1997 and 2000, inclusive. Using the heuristic branching rule, the 1997–2000 subset is selected for evaluation. The network model is formulated with the acquisition and OMR cost approximation. Solution indicates that all plans in the subset are infeasible: system capacity is insufficient if the site is acquired between 1997 and 2000. Thus all capacity-expansion plans in this subset are eliminated from further consideration.

When a subset of plans is eliminated, the procedure is to backtrack. So in iteration 3, 1981–1996 acquisition is evaluated. The network model is formulated and solved to evaluate approximately the cost for plans in this subset, and a lower bound of $23,500,275 is computed.

By following the heuristic rules, the 1981–1996 subset is divided into a 1981–1989 subset and a 1990–1996 subset. The 1990–1996 subset is selected for further investigation in iteration 4, and system operation is analyzed with the network model for plans in this subset. The lower bound on cost is $23,515,395.

For iteration 5, the 1990–1996 subset is divided into a 1990–1993 subset and a 1994–1996 subset, and the 1994–1996 subset is selected for evaluation. Execution of the network model indicates that plans in the 1994–1996 subset are not feasible, so all are eliminated from further consideration. The analysis backtracks, and the 1990–1993 subset is evaluated in iteration 6. The estimated lower bound is $23,661,624.

After several iterations, the set of plans is separated into 1990–1990 and 1991–1991 subsets. These subsets include only a single capacity-expansion plan. The 1991 acquisition plan is evaluated and is found to be infeasible. The 1990 plan is feasible, and the lower bound of the subset is $23,786,139. This plan is now a trial optimal plan. If the lower bound of any subset subsequently evaluated exceeds the cost of this trial optimum, all plans in that subset are eliminated from consideration. This the case in iteration 11; the lower bound on 1981–1989 capacity expansion plans, $23,909,040, exceeds the trial optimum. Thus all expansion plans in that subset are eliminated, leaving the plan identified in iteration 10 as the optimal plan.

Role of the Models in Plan Formulation

Systems analysis tools can play an important role in water resources planning when those tools are used as a source of information for the planning professionals. The models developed for and used in this study are viewed as filling that role. The attractiveness maps are not considered as the source of all wisdom; alternative sites, identified from experience, are considered along with those identified with those maps. The geographic information system and the attractiveness maps serve only to systematize the discovery of sites that might otherwise have been ignored. Likewise, the results of the analytical optimization models are not treated as a result of divine revelation. All professionals involved in the planning realize that, by necessity, the mathematical representation of the disposal system is a simplification of the real-world system. Consequently, the "optimal" decisions identified by the models are viewed as guidelines for those decisions that must ultimately be made for operation and expansion of the Delaware River dredged-material disposal system.

Conclusions

An ensemble of analytical tools is used to identify feasible capacity expansion plans for the Delaware River dredged-material disposal system. Critical spatially-oriented attributes of the river and adjacent area are stored with a geographic information system. Attractiveness maps produced with these attributes help to identify a set of potential expansion sites. The least-costly combination of these potential sites and the best sequence for acquisition is identified with a branch-and-bound enumeration procedure. This simple, systematic procedure permits direct use of a network-flow programming model for cost evaluation.

Acknowledgments

The capacity-expansion and network models described herein were developed by the writer, Darryl Davis, and Shelle Barkin at the Hydrologic Engineering Center, USACE, with assistance from Brian Heverin and the staff of the Philadelphia District, USACE. Gary Rohn and Frank Schaeffer of the Philadelphia District provided details of the site-attractiveness study. Tom Walski of the Waterways Experiment Station, USACE, reviewed this paper and suggested improvements.

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Appendix II.—Notation

The following symbols are used in this paper:

$ACQCST(J)$ = acquisition cost of site J;
$ATB(I,J,K)$ = coded value of attribute K for grid cell in row I, column J;
$F_K(\ )$ = a transformation function for attribute K;
I = index of row in grid-cell data base;
$INDEX(I,J)$ = attractiveness index of grid cell in row I, column J;
$IPER1$ = base period for economic analysis;
$IPERA(J)$ = initial period for acquisition of site J for any plan in the subset;
$IPERB(J)$ = last period for acquisition of site J for any plan in the subset;
J = index of column in grid-cell data base, also index of disposal site;
K = index of attribute;
$NATB$ = total number of attributes stored for each grid cell;
$PWF(R, T - IPER1)$ = present-worth factor, by which cost at period T is converted with interest rate R to equivalent initial cost in period $IPER1$;
$S(J,T)$ = volume of material stored in site J at end of period T;
$SMAX(J)$ = capacity of disposal site J;
$VC(J)$ = unused volume per unit cost for site J; and
$WT(K)$ = weight assigned for attribute K in the ranking of attributes (may be zero if attribute is not considered).

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