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Hydrologic Engineering Center

Dredged-Material Disposal Management Model

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To identify efficient dredged-material disposal management strategies for the Delaware River navigation system near Philadelphia, the system operation problem is formulated and solved as a generalized minimum cost network flow programming problem. This formulation represents material sources and available disposal sites as nodes of the network and transportation links and carry-over storages as arcs. The dewatering, consolidation, and densification of dredged material is modeled with an arc gain factor, thereby allowing reduction of the total volume of material within the network but requiring use of a network-with-gains algorithm for solution of the operation problem. Application of the model defines cost-efficient dynamic schemes for allocation of material to available disposal sites. A generalized computer program was developed to define automatically the nodes, arcs, and parameters of the arcs of the network, given a description of the dredged-material disposal system. Structured analysis and structured programming techniques were used, thus providing a clear definition of the computations required, the order in which they must be accomplished, and the flow of data. This software development technique reduces the effort required for subsequent modification of the program to analyze the system capacity-expansion problem.

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Dredged-Material Disposal Management Model

David T. Ford[1], M. ASCE

Abstract

To identify efficient dredged-material disposal management strategies for the Delaware River navigation system near Philadelphia, the system operation problem is formulated and solved as a generalized minimum cost network flow programming problem. This formulation represents material sources and available disposal sites as nodes of the network and transportation links and carry-over storages as arcs. The dewatering, consolidation, and densification of dredged material is modeled with an arc gain factor, thereby allowing reduction of the total volume of material within the network but requiring use of a network-with-gains algorithm for solution of the operation problem. Application of the model defines cost-efficient dynamic schemes for allocation of material to available disposal sites. A generalized compute program was developed to define automatically the nodes, arcs, and parameters of the arcs of the network, given a description of the dredged-material disposal system. Structured analysis and structured programming techniques were used, thus providing a clear definition of the computations required, the order in which they must be accomplished, and the flow of data. This software development technique reduces the effort required for subsequent modification of the program to analyze the system capacity-expansion problem.

Delaware River Disposal Management Problem

Background. - The Corps of Engineers has been responsible for maintenance of the navigable waterways of the United States singe 1824. The maintenance includes excavation and disposal of the sediment deposited in the waterways. Current common practice is to excavate the material with a mechanical or hydraulic dredge (10) and to transport it to a disposal site either by pumping through a pipeline or by carrying the material to the site in barges or in hoppers on the dredge. The disposal site may be an offshore site selected to minimize interference with navigation or the disposal site may be a contained upland site. Contained disposal sites are natural or manmade ponding areas into which the dredged material is pumped or lifted. In the disposal site, water gradually drains and evaporates from the dredged material, and the solids densify and consolidate. The rate of dewatering, densifying, and consolidating can be increased by surface trenching, wicking, surcharging, and pumping with well pants. Detailed descriptions of these techniques and other technical aspects of dredged-material management are presented in Reference 3 and in associated reports of the Corps' Dredged Material Research Program.

Management of the long-term operation of a dredged-material disposal system requires selection of the equipment to be used for excavating and transporting the material from the channel to the disposal sites, allocation of the capacity of the available disposal sites to satisfy the demand for storage imposed by the dredging operation, selection of appropriate disposal-site management practices, and identification of capacity expansion schemes if the system capacity is exhausted at some time. Due to the complexity

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of the long-term problem, equipment selection and capacity allocation generally is addressed only for the short-term, with equipment and sites selected for minimum cost at the time the dredging is performed. Physical and environmental limitations may constrain this selection and allocation. Likewise, problems of disposal-site operation and of capacity expansion generally are addressed with heuristic rules as problems arise.

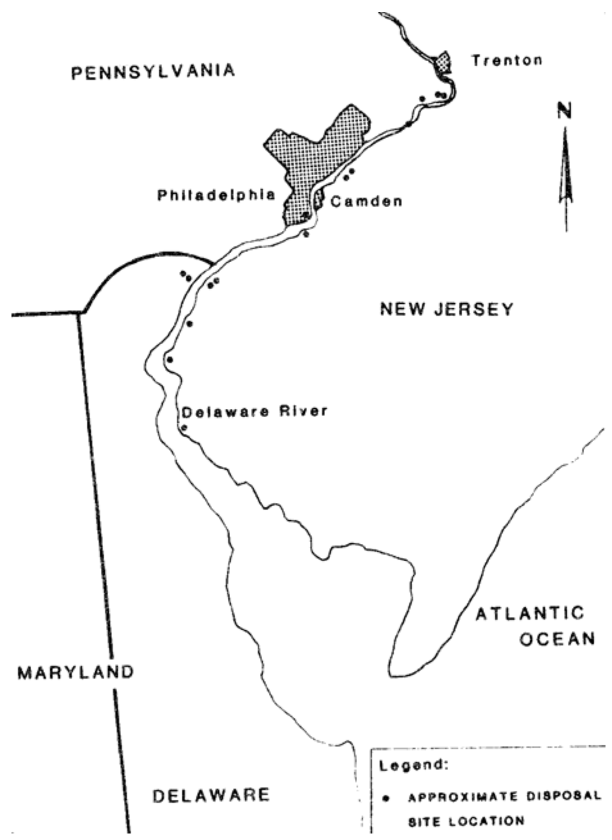

Figure 1 Delaware River System

Delaware River System. - The Delaware River, Delaware Bay, and associated tributaries are maintained in a navigable condition by the Philadelphia District, Corps of Engineers. Within this area, shown in Figure 1, twenty-three Federal navigation projects yield approximately 8,100,000 cu yd (6,200,000 m^3) of dredged material annually. Non-Federal maintenance dredging contributes an additional 3,400,000 cu yd (2,600,000 m^3). The material is disposed in twenty-one containment sites. According to estimates published in a 1979 study, by 1999 all these sites will be filled or unavailable due to lease expiration with continued maintenance dredging at current rates and with no change in management practices (4). This in turn would mean reduction or cessation of dredging and consequent reduction or cessation of navigation. The 1979 study identifies a number of management alternatives that may be employed, including:

1. Capacity expansion alternatives: (a) Acquisition of new upland sites; (b) open-water disposal of dredged material; and (c) extension of leases on sites.
2. Operation alternatives: (a) Dewatering of disposal sites; (b) increase in containment dike height; (c) reuse of dredged material; (d) reduction of maintenance dredging; (e) use of deposition basins to reduce shoaling; (f) reduction of sediment erosion; and (g) improvements in site management.

Management Model Description

Model Objective. - The dredged-material disposal management model was developed for systematic evaluation of and comparison of alternative management schemes. With the mode, capacity expansion alternatives can be analyzed, and the minimum-cost combination and schedule can be determined for new site acquisition and lease extension. Also, the minimum-net-cost operation policy for any specified system can be determined. This policy is required both for long-term system operation planning and for solution of the expansion problem; the total cost of any alternative capacity expansion scheme is a function of site acquisition, lease extension, and operation costs. The minimum operation cost and the associated operation policy are determined by formulating a mathematical programming model that represents the problem of allocating efficiently the available capacity. Disposal-site dewatering rates, containment dike heights, and other characteristics of the disposal system are specified by the model user, so management schemes that involve changes in these parameters are evaluated by systematic variation and re-execution of the model.

Initial development of the disposal management model is limited to formulation of the mathematical programming model presented herein for analysis of operation of a defined system. Ultimately the model will be expanded to address the capacity expansion problem, using a branch-and-bound algorithm which iteratively enumerates a limited number of alternative site acquisitions and lease renegotiation schemes, evaluates the efficiency and feasibility with the operation model, and identifies efficient schemes for expanding the system. The branch-and-bound procedure provides rules for eliminating from consideration many costly or infeasible schemes without actual evaluation with the operation model.

Mathematical Programming Formulation. - The mathematical programming formulation of the dredged-material disposal system operation problem includes continuity constraints for material sources and for disposal sites, transportation link and disposal-site capacity constraints, and carry-over storage constraints. The continuity and capacity constraints define the operation problem for each period. The carry-over storage constraints relate conditions within each period, yielding a multi-period operation problem. Unit costs are associated with transportation and disposal of dredged material. The objective is to minimize the total discounted cost of system operation. This formulation is similar to the solid-waste disposal model formulated by Marks and Liebman (13) and to the wastewater disposal model formulated by Brill and Nakamura (2).

A continuity constraint is included for each material source and for each disposal site for each period of analysis. The form of the equation for each material source, *I*, for each period *T* is:

$$\sum_{J=1}^{NDISP} F(I,J,T) = V(I,T) \tag{1}$$

in which:

J = index of disposal sites
NDISP = total number of disposal sites
F(I,J,T) = volume of material transported from source *I* to site *J* in period *T*
V(I,T) = total volume of material dredged at source *I* during period *T*

The forms of the equation for each disposal site *J* for each period *T* is:

$$S(J,T-1) + VF(J)^{*}\left[\sum_{J=1}^{NDRG} F(I,J,T)\right] + \left[\sum_{\substack{J'=1\\ J'\neq J}}^{NDISP} RT(J',J,T) - RT(J,J',T)\right] - RU(J,T) = S(J,T) \tag{2}$$

in which:

NDRG = total number of dredged-material sources
S(J,T-1) = volume of material stored at site *J* at beginning of period *T* an at the end of period *T-1*
S(J,T) = volume of material stored at site *J* at end of period *T*
RT(J,J',T) = volume of material transferred to site *J* from site *J'*
RT(J',J,T) = volume of material transferred from site *J* to site *J'* in period *T*
RU(J,T) = volume of material from site *J* removed and sold for reuse
VF(J) = an average volume-reduction factor.

The volume reduction factor reflects: (1) the wet-to-dry volume ratio of the dredged material; and (2) the efficiency of the disposal site management practices. The wet-to-dry volume ratio defines the average volume of dry material per time period that must be stored at the disposal site as a fraction of the total volume of material in situ. E.g., a wet-to-dry ratio of 2.0 indicates that the dredged material, when wet, will occupy twice the volume occupied by the dried material. In this formulation the volume reduction is assumed to occur within one period. The efficiency of the disposal site in terms of achievement of the reduction depends on the site management techniques. If the techniques employed are one-hundred percent efficient, *VF(J)* will equal the reciprocal of the wet-to-dry ratio; otherwise, *VF(J)* will equal the product of this reciprocal and the estimated efficiency of the dewatering techniques used at the site. Typical values of *VF(J)* range from 0.50 to 1.00.

The total volume of material to be transported to or from a disposal site is constrained by the characteristics of the pipeline, hopper, or other device used for transportation. Likewise, the volume of material deposited at a site each period *T* is constrained by the size of the site. These limitations are expressed mathematically as:

$$F(I,J,T) \le FMAX(I,J) \tag{3}$$

$$RT(J,J',T) \le RTMAX(J,J') \tag{4}$$

$$RU(J,T) \le RUMAX(J) \tag{5}$$

$$S(J,T) \le SMAX(J) \tag{6}$$

in which:

FMAX(I,J) = capacity of the transportation link between dredged-material source *I* and disposal site *J*
RTMAX(J,J') = capacity of the facilities for removing material from disposal site *J* and transferring it site *J'*
RUMAX(J) = capacity of the facilities for removing material from disposal site *J* for reuse
SMAX(J) = storage capacity of disposal site *J*

In addition to the restrictions on transportation, disposal-site management practices may pose a limitation on the rate of addition of "wet" material to the site. This limitation is imposed each period by the following constraint:

$$\sum_{I=1}^{NDRG} F(I,J,T) \le ADDMAX(J) \tag{7}$$

in which:

ADDMAX(J) = maximum allowable volume addition per period

The operation problem is to determine the "best" scheme for allocating the material dredged each period to the available sites over the planning horizon. The efficiency of operation is defined as the algebraic sum of present value of costs of disposal and transportation and the benefits of reuse. Mathematically, this is expressed as

$$Z = \sum_{T=1}^{NPERS} (1+R)^{-T} \left[\left\{ \sum_{I=1}^{NDRG} \sum_{J=1}^{NDISP} CF(I,J) * F(I,J,T) \right\} + \left\{ \sum_{J=1}^{NDISP} CS(J) * \sum_{I=1}^{NDRG} F(I,J,T) \right\} + \right.$$

$$\left\{ \sum_{J=1}^{NDISP} \sum_{\substack{J'=1 \\ J' \neq J}}^{NDISP} CRT(J,J') * RT(J,J',T) \right\} - \left\{ \sum_{J=1}^{NDISP} CRU(J) * RU(J,T) \right\} \Bigg] \tag{8}$$

In which:

Z = the present value of system net benefits for the period of analysis
R = discount rate
NPERS = number of time intervals
CF(I,J) = unit cost of transporting material from dredge site *I* to disposal site *J*
CS(J) = unit cost of adding material to disposal site *J*
CRT(J,J') = unit cost of removing material from site *J*, transporting to and disposing in site *J'*
CRU(J) = unit benefit of reuse of material from site *J*.

These costs and benefits are assumed to be constant over time. The objective is minimization of the net cost, *Z*.

Mathematical Programming Problem Solution. - The dredged-material system operation model as presented includes linear constraints and a linear objective function, so a linear programming (LP) algorithm can be used to determine the optimal allocation of dredged material to the available sites. However, the constraints define only conservation requirements and transportation limitations, and the costs and benefits are functions of the volume of material transported or stored, so the operation problem can be formulated as a network-flow programming problem. In a network-flow problem, the decisions required are visualized as flows in the arcs connecting the nodes of a network, and the objective is to choose the flow in each arc to optimize some efficiency measure, such as total cost. The arcs of the network are characterized by the allowable direction of flow, the maximum and minimum amounts of flow that can pass through each arc, the unit cost of use of the arc, and a gain that represents the fraction of flow that is lost (or gained) in each arc. The constraints are limited to conservation of flow at the nodes of the network and to upper and lower bounds on flows in the arcs. Algorithms for solution of the network-flow problems are more efficient than those for solution of the general LP problems. Ford and Fulkerson (8) and Jensen and Barnes (12) provide detailed descriptions of the characteristics of network-flow problems.

The network-flow model of the disposal operation problem represents material sources and available disposal sites as nodes and transportation links and carry-over storage as arcs. The network representation of a small disposal system is shown as Figure 2. Nodes 1 and 2 represent the Pedricktown North disposal site, nodes 3 and 4 represent the Pedricktown South site, and nodes 5 and 6 represent Overflow Site 1. Nodes 7, 8, and 9 represent the Marcus Hook, Bellevue, and Cherry Island dredge sites, respectively. The arcs connecting nodes 7, 8, and 9 with nodes 1, 3, and 5 represent the transportation links between the material sources and disposal

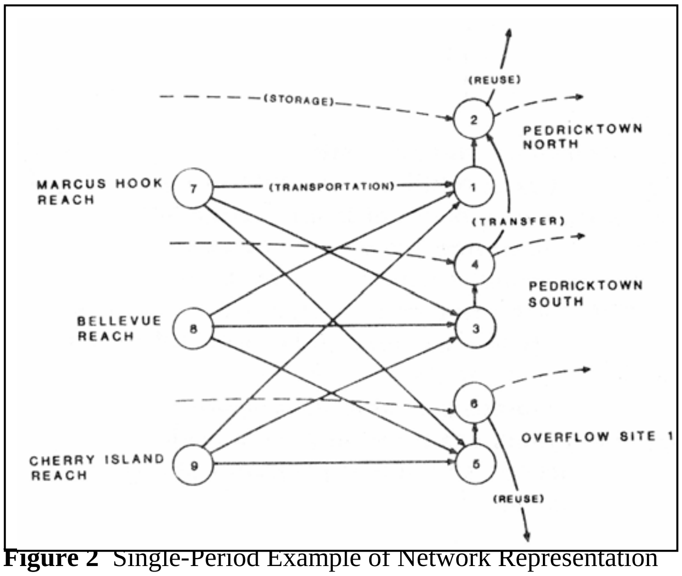

Figure 2 Single-Period Example of Network Representation

sites. The "flows" in these arcs represent the volumes of material allocated to the disposal sites. For a more complex system, arcs are included to connect each source with each site available for disposal of the material from that source. An upper bound is imposed on flow in these arcs, as dictated by the transportation method represented.

Removal of material from the disposal sites for reuse is represented by an arc originating at the disposal site node and terminating at a node that represents the point of sale of the reused material. Material removed from the Pedricktown South site and transferred to the Pedricktown North site is represented by flow in the arc originating at node 4 and terminating in node 2.

The arc originating at node 1 and terminating at node 2, the arc originating at node 3 and terminating at node 4, and the arc originating at node 5 and terminating at node 6 are included as a computational mechanism to represent the drying of material added to a disposal site and to limit the rate of addition of material to the site. The gains for these arcs are the volume reduction factors [*VF(J)* of Equation 2], and the upper bounds are the maximum allowable rates of disposal [*ADDMAX(J)* of Equation 7].

Material is introduced to the network at the nodes that represent the dredged-material sites. In the terminology of Jensen and Barnes (12), these volumes are node external flows; the quantity of flow entering the network is fixed.

The dashed arcs of Figure 2 represent the storage of material in the system disposal sites. The flow in the storage arc that terminates at node 2 represents the net volume of dried material deposited in the Pedricktown North site in all periods prior to the current period [*S(J,T-1)* of Equation 2]. The storage arc originating at node 2 represents the cumulative volume of dried dredged-material deposited in the site after the addition and removal of material in the period shown [*S(J,T-1)* of Equation 2]. When the network is expanded for analysis of multiple-period operation, these storage arcs link the networks that represent single-period problems. This is shown in Figure 3.

A unit cost is associated with the flow in each arc; the objective of the solution algorithm is to determine the allocation of flow to the various network arcs to minimize the sum of the product of flow in each arc and the corresponding cost. The unit costs assigned to the network arcs are the discounted units costs of storing, transporting, or re-handling material [*CS(J)*, *CF(I,J)*, and *CRT(J,J')* of Equation 8] and the negative of the unit benefit of reuse [*CRU(J)* of Equation 8].

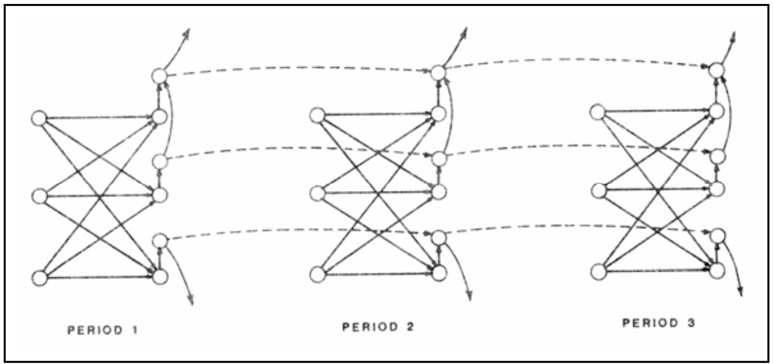

Figure 3 Multiple-Period Network Representation

The traditional network flow programming solution algorithms, such as the out-of-kilter algorithm (5,7,9) were developed for problems in which all gain factors are unity and, thus, are not applicable. Consequently, for solution of the management problem as formulated, a specialized network-with-gains algorithm is employed. This algorithm solves the generalized minimum-cost network flow problem with any nonnegative gain factors using a flow-augmentation algorithm. In this application, the algorithm begins with flow in all arcs set equal to zero. The minimum cost per unit of additional flow to each node of the network and the path over which that flow may be obtained is determined. The total flow through the network is increased along the minimum-cost path until the flow in one or more arcs in the path exceeds the bounds. This process continues iteratively until the required system input flows are satisfied or a maximum possible flow through the network is obtained. This algorithm guarantees achievement of a feasible, global optimal solution if such a solution exists. Additional details of the algorithm are presented by Jensen and Bhaumik (11) and by Jensen and Barnes (12); a previous application of the algorithm is described in Reference 14.

Software Development

A generalized computer program was developed to implement the proposed disposal-system management model to evaluate alternative system capacity expansion plans. The program development employed state-of-the-art software engineering techniques, including structured analysis and structured programming (1).

Structure Analysis. - Structured analysis is a logical process for transforming information about program requirements into specifications for the program that is to be developed. This approach is contrary to usual engineering program development activities in which everyone eagerly gets on the "real" work - writing code. As described by Demarco (6), the structured analysis approach has the following characteristics: (1) it yields a paper model of the program-to-be; (2) the program is designed in a top-down, hierarchical fashion with a smooth progression from abstract definition of program components to a detailed definition; (3) it yields a set of connected "mini-specifications" of the identified program components; and (4) it uses diagrams for communication of ideas, especially between the program user, program designer, and computer system analyst.

Top-down program design begins with the establishment of firm requirements for the tasks to be accomplished by the program and with the definition of data required to accomplish the tasks. The overall program structure (top-level) is then defined, with progressive refinement of lower-level components of the program. Figure 4 shows the organization of the top level of the dredged-material disposal management program. The program consists of an "executive" routine controlling an "input", a "process", and an "output" routine. Figures 5 and 6 show further refinement of the process component; specification of the other components is refined in a similar manner. Development of the system management model was planned (and funded) for completion in two separate stages: Stage 1 includes only the operation model development, while Stage 2 addresses the capacity expansion problem in more detail. In Stage 1, several of the components shown were defined only in conceptual terms. For example, detailed specification of computational techniques was delayed initially in the case of component 3.1. Nevertheless, the data transfers and the required results of execution of each module were defined.

The network-flow programming model formulated to determine the optimal allocation of dredged material is identified as component 3.3.4 in Figures 6 and 7. As one of the goals of program development is to produce a management model usable by engineers and planners who are not familiar with mathematical programming techniques, component 3.3.4.1 is included here to translate disposal-system descriptive data into the node-arc representation. The resulting generalized minimum-cost network-flow problem is solved with code included in component 3.3.4.2. Definition of this component is further refined to include components of the network-with-gains algorithm.

Structured Programming. - The actual computer code to implement the disposal management model was developed from the structured analysis using structured programming techniques. Each of the components was translated into one or more subprograms that perform independently single tasks required for solution of the operation problem. The benefits of this approach are: (1) the actual development time is reduced because a number of programmers may simultaneously develop the modules, or existing code may be used easily; (2) complex programs may be tested in parts, with each module verified independently; (3) the code is easier to understand and to maintain; (4) the resulting code is flexible and may be modified by changing single modules independently; and (5) documentation of the code is easier. Items 3, 4, and 5 are significant given the environment within which the computer code described here will be used. Although a single application motivated development, application to other disposal operation problems is likely and despite careful program design, past experience indicates a frequent need for special-case modification. Often these modifications must be performed by someone other than the original program writer, thus the need for understandable code.

Application

Operation Evaluation. - The operation model has been used to evaluate the operation of various existing and proposed configurations of the Delaware River dredged-material disposal system, including the subsystem between Philadelphia and the sea. As modeled, this subsystem includes nineteen dredge sites and eight disposal sites (of which two are imaginary sites for overflow if the system capacity is insufficient). Pertinent data describing the disposal sites are presented in Table 1. Material is dredged at average annual rates shown in Table 2 and is transported by barge, hopper, or pipeline to the disposal sites. The dredging and transporting costs depend on the machinery used and the distance which the material is transported; costs vary from $1.62 to $25.00/cu yd and are shown in Table 3. The unit costs of placing the material in the system disposal sites vary from $0.00 to $0.50/cu yd, as indicated in Table 1.

Disposal Site (1)	Capacity Remaining, in cubic yards (2)	Wet-to-dry Ratio (3)	Disposal Cost, in dollars per cubic yard (4)
Artificial Island	16,500,000	1.50	0.32
Overflow Site 1	99,000,000	1.00	0.00
Overflow Site 2	99,000,000	1.00	0.00
National Park	7,100,000	1.50	0.50
Killcohook	36,900,000	1.50	0.11
Penns Neck	16,000,000	1.50	0.25
Pedricktown North	21,700,000	1.50	0.16
Pedricktown South	21,700,000	1.50	0.17

Note: 1 cubic yard = 0.765 m^3; 1 acre = 0.405 ha

The operation of the Philadelphia-to-sea subsystem was analyzed for fifty years using twenty-five consecutive two-year intervals. The resulting network consisted of 877 nodes and 3,709 arcs. Time required for definition of the network parameters and for solution of the minimum-cost optimization program on a commercial CYBER 175 computer system used by the Corps was approximately 59 CP seconds. The minimum present-value net cost for system operation with an annual discount rate of 7 5/8% is $\$273 \times 10^6$.

Figures 8-11 are reproductions of portions of the computer program output. Figure 8 is a summary of the dimensions of the system to be analyzed. Also, for each type of dredge, a function relating the unit excavating and transporting cost to distance transported is presented. Figure 9 is one of eight disposal site reports. In this report, the physical and economic characteristics of the disposal site are summarized. Site acquisition and lease renegotiation data are included for future use when the program is expanded to address the capacity expansion problem. Figure 10 is one of nineteen dredge site reports for this system. The alternative sites for disposal of material are shown, and the capacity and the unit cost of excavating

Dredge Site (1)	Volume (2)
Eddystone	12,300
Chester	890
Marcus Hook	1,850,300
Bellevue	49,900
Cherry Island	180,900
Deepwater Point	1,402,900
Bulkhead Bar	28,700
Newcastle	1,269,400
Reddy Island	28,000
Baker	10,800
Liston	220,800
Miah Maull	41,000
Brandywine	1,500
W. Horseshoe	25,800
Mifflin	67,400
Billingsport	5,600
Tinicum	43,200
Upper Philadelphia Harbor	6,500
Lower Philadelphia Harbor	181,500

Note: 1 cubic yard = 0.765 m^3

	Disposal Site							
Dredge Site (1)	**Artificial Island (2)**	**Overflow Site 1 (3)**	**Overflow Site 2 (4)**	**National Park (5)**	**Killcohook (6)**	**Penns Neck (7)**	**Pedricktown North (8)**	**Pedricktown South (9)**
Eddystone	6.99	25.00	25.00	17.89	****	****	2.83	3.06
Chester	6.57	25.00	25.00	*****	****	****	2.42	2.65
Marcus Hook	6.12	25.00	25.00	17.01	****	****	1.99	2.22
Bellevue	4.91	25.00	25.00	*****	****	2.47	2.09	1.86
Cherry Island	****	25.00	25.00	15.40	****	2.08	2.48	2.25
Deepwater Point	3.57	25.00	25.00	*****	2.01	1.95	***	3.23
Bulkhead Bar	3.16	25.00	25.00	*****	1.61	2.35	***	***
Newcastle	2.48	25.00	25.00	*****	1.98	3.02	***	***
Reddy Island	1.62	25.00	25.00	*****	2.84	3.90	***	***
Baker	1.63	25.00	25.00	*****	3.25	4.29	***	***
Liston	2.22	25.00	25.00	*****	3.85	4.86	***	***
Miah Maull	7.25	19.25	19.25	*****	8.88	9.94	***	***
Brandywine	8.70	15.24	15.24	*****	10.33	11.36	***	***
W. Horseshoe	8.56	25.00	25.00	19.30	****	****	4.37	4.60
Mifflin	8.09	25.00	25.00	19.02	****	****	3.93	4.15
Billingsport	7.85	25.00	25.00	18.78	****	****	3.69	3.93
Tinicum	7.23	25.00	25.00	18.14	****	****	3.07	3.31
Upper Philadelphia Harbor	9.69	25.00	25.00	19.30	****	****	5.50	5.75
Lower Philadelphia Harbor	9.24	25.00	25.00	19.30	****	****	5.29	5.04

Note: * indicates sites not linked (1 cubic yard = 0.765 m^3)

and transporting material to each site are tabulated. (The unit cost is determined from the appropriate unit cost versus distance function.) The estimated volumes of material to be removed each period are shown. (Note that the value shown for each period in Figure 10 is twice the corresponding value from Table 2 because each period in the analysis corresponds to two years.)

The results of optimal operation of the dredged-material disposal system are presented as a tabulation of material added to each disposal site each period and of end-of-period storage and the corresponding elevation and surface area. Figure 11 is an example of the tabulation for one site. The results of the minimum-cost operation are summarized in Table 4. All disposal sites except the overflow sites will be filled by the end of the fifty-year model. Overflow Site 1 is used initially in the ninth two-year interval, indicating that system capacity falls short of demand within eighteen years of the first year. This conclusion is significant but is difficult to draw with traditional mass analysis techniques because of the complex interconnections.

Systematic Evaluation of Operation Alternatives. - Evaluation of disposal site management alternatives is accomplished by systematic application of the operation model with variation of the appropriate input parameters. For example, to evaluate the cost effectiveness of use of trenching devices that speed the drying of deposited material in the disposal sites, the volume-reduction factor, VF(J), and the maximum allowable volume addition per period, ADDMAX(J), are changed to reflect the improvement possible, and the disposal cost, CS(J), is altered as appropriate. The operation problem is resolved to determine the least-costly operation scheme. The cost of the trenching machinery is added to the operation cost to determine the total system cost. This total cost is compared with the total cost without the trenching devices; if the cost is less, the trenching device is cost effective.

Any management alternative can be evaluated by systematic analysis with the operation model, if the improvements attributable to that alternative can be expressed in terms of the volume-reduction factor, maximum allowable addition per period, maximum storage, capacity of transfer facilities, capacity of reuse facilities, or the time at which facilities are available. Techniques that alter the volume of time distribution of dredged material that must be disposed can be analyzed in the same systematic manner because the volumes are specified by the user for each period.

Conclusions

To identify efficient dredged-material disposal management strategies, the system operation problem can be formulated and solved as a generalized minimum-cost network flow programming problem. In this formulation, the material sources and disposal sites are represented as nodes, and the transportation links and carry-over storages are represented as arcs. The network-with-gains algorithm is used for solution, thereby allowing modeling of the drying material in the disposal sites.

The proposed disposal system operation model can be used for the evaluation of alternative management schemes by systematically varying the appropriate model parameters, re-executing the model, and comparing the net operation cost to determine the effectiveness of the scheme. In the future, this model will be linked with a branch-and-bound algorithm to identify efficient disposal system expansion schemes.

A generalized computer program to implement the proposed operations model was developed using software engineering methods. Structured analysis techniques were used to define the program requirements, and structured programming was used to transform the requirements into executable computer code.

The dredge-material disposal management model has been used successfully to evaluate the operation of the Delaware River disposal system.

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Notation

The following symbols are used in this paper:

ADDMAX(J) = maximum allowable volume addition per period, site J;

CF(I,J) = unit cost of transporting material from source I to disposal site J;

CRT(J,J') = unit cost of re-handling material from disposal site J to site J';

CRU(J) = unit benefit of reuse of material from site J;

CS(J) = unit cost of adding material to site J;

F(I,J,T) = volume of material transported from source I to site J in period T;

FMAX(I,J) = capacity of transportation link between dredged-material source I and disposal site J;

NDISP = number of disposal sites;

NDRG = number of dredged-material sources;

NPERS = number of the periods;

RT(J,J',T) = volume of material transferred from site J to site J', period T;

RTMAX(J,J') = capacity of transfer facilities between site J and site J';

RU(J,T) = volume of material removed from site J and sold for reuse, period T;

RUMAX(J) = capacity of ruse facilities, disposal site J;

S(J,T) = volume stored in disposal site J, period T;

SMAX(J) = capacity of disposal site J;

V(I,T) = total volume of material dredged at source I during period T;

VF(J) = volume reduction factor, disposal site J; and

Z = net system operating cost.

Subscripts

I = dredged-material source;

J = disposal site, and

T = time period.

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