# Dredged Material Disposal Economics

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**Abstract:** Recent difficulties in siting dredged material disposal facilities are increasing interests in alternative disposal or reuse of dredged material and the possible adverse consequences of any increases in the generation of dredged materials. This paper focuses on economic aspects of these issues. Simple methods are suggested for evaluating the economics of increasing or decreasing the rate of disposal of dredged material into a disposal site with a limited volume. These simple methods apply to common special cases. A more elaborate linear programming method is suggested for consideration and scheduling of several disposal alternatives. These methods are illustrated by examples and their limitations are discussed.



## Introduction

The difficulty of siting new disposal facilities for dredged material has become a major impediment for both maintenance and new-work dredging operations. Increases in the value of land, increasing concern for wetland and environmental impact, and the exhaustion of convenient disposal sites have all combined to make the development of new disposal sites for dredged material more controversial and expensive. This increase in the costs of siting new facilities has increased interest in alternatives to traditional upland or aquatic disposal of dredged material (Landin and Smith 1987; Lazor and Medina 1990). Disposal concerns have also affected consideration of the scheduling and operation of maintenance dredging activities. Expansion of existing dredged waterways, either as part of general project expansion or to implement advance maintenance dredging, can imply a need to dispose of increased volumes of sediment (Lund 1989b; Trawle and Boyd 1988). Beyond its application to navigation projects, this disposal problem is also relevant to the disposal of dredged material from reservoirs (Roberts 1976).

This paper suggests two methods for the economic evaluation of dredged material disposal options and changes in annual disposal rates. The difficulty here lies in evaluating the economic consequences of changes in disposal rates resulting in accelerating or deferring exhaustion of existing dredged material disposal sites and coordinating traditional and new disposal options.

The methods presented here apply to common special cases of dredged material disposal optimization done by the Corps of Engineers (Ford 1984, 1986). Here, only a single existing disposal site is considered. This disposal site is to be replaced by some known other site or alternative means of dredged material disposal. The focus of this paper is not the least-cost planning of future disposal capacity, but the least-cost plan for changes in dredging operations and alternatives to disposal that have economic effects on the disposal system.

The environmental quality effects of changed annual disposal volumes of dredged material, while of overriding importance in many cases, are con-

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Note. Discussion open until December 1, 1991. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on September 6, 1990. This paper is part of the ***Journal of Waterway, Port, Coastal, and Ocean Engineering***, Vol. 117, No. 4, July/August, 1991. ©ASCE, ISSN 0733-950X/91/0004-0390/$1.00 + $.15 per page. Paper No. 26015.



J. Waterway, Port, Coastal, Ocean Eng. 1991.117:390-408.

sidered to be largely separable from economic evaluation and are not addressed here. Often, they can be represented as constraints in the methods developed in this paper.

## Changes in Annual Dredged Material Disposal Rates

Changes in annual volumes of dredged material disposal (a.k.a., disposal rates) can result from several causes. Increases in these disposal rates can result from new or expanded navigation projects. Increased annual disposal rates can also sometimes result from employment of advance maintenance dredging to reduce the costs of dredging, in cases where sedimentation rates increase with dredged depth (Lund 1989; Trawle and Boyd 1988). This accelerated sedimentation would result in accelerated exhaustion of existing and planned dredged material disposal capacity.

Decreases in dredged material disposal rates are often contemplated for extending the operational lifetime of existing and hard-to-replace disposal sites. Such decreases usually require some alternative use for the dredged material or possibly some long-term reduction in maintenance dredging. Alternatives that have been considered include land reclamation, aquatic habitat development, agricultural land improvement, beach nourishment, levee construction, and use in construction materials (Landin and Smith 1987; Lazor and Medina 1990).

Changes in annual disposal rates are felt both in terms of operating costs for transportation and placing dredged material and in terms of capital costs for eventual replacement of exhausted disposal sites. The costs of transporting and placing dredged material at existing and potential new disposal locations is relatively well known from experience (Souder et al., 1978). The value of accelerating or deferring acquisition of a new disposal site is more difficult to estimate. The remainder of the paper describes an array of methods available for economic consideration of changes in disposal rates of dredged material.

## Least-Cost Disposal Planning for Large Projects

Ford (1984) examines the problems of economically allocating dredged material from a series of dredged reaches among a series of dredged material disposal sites. Ford (1986) later integrates this work with the optimal planning of present and future disposal sites for a large dredged navigational system. Mathematical programming is used to address both these problems. The least-cost allocation of dredged material among disposal sites and dredged material reuse options is found using network flow programming. This formulation incorporates a plan for the acquisition of future disposal sites (Ford 1984). The least-cost disposal site acquisition plan is found using branch-and-bound enumeration (Ford 1986) together with the network flow program solution from his earlier work. This combination of optimization models allows for the least-cost planning of a combination of existing and potential disposal sites together with dredged material alternative use (reuse) options over a long period of time.

This work, while an excellent approach for disposal planning on large navigational systems, can be greatly simplified for small navigational systems with a single disposal site, multiple alternative uses for dredged material, and a single option for a new disposal site. This paper develops formulations and solutions for these common simpler problems.

## Turvey Marginal Cost

The theory of marginal cost developed by Turvey (1969) can simplify this problem for consideration of disposal rate changes for small systems. This approximate method is based on the idea of marginal cost as defined by Turvey (1971):

> Marginal cost is the difference between two time streams of minimum total cost, each corresponding to a different level of demand . . . if linear programming is used to minimize total costs, marginal cost is conveniently measured by the duals of the demand constraints.

In this quote, Turvey develops a sophisticated idea of marginal cost for economic analysis of public enterprises. This idea can provide preliminary economic evaluations of changes in dredged material disposal rates into a traditional disposal site. Here, marginal cost consists of the difference in the present value of disposal costs for unit changes in the annual dredged material disposal rate.

The case of a system with a single traditional disposal site of limited capacity is considered. Currently, dredged material is disposed of at the site at a rate of $Q_D$ per year. After the disposal site is filled, a new site must be acquired at a cost of $C_R$ at the time of acquisition. Increasing the disposal rate accelerates the exhaustion of the site and moves the cost of replacing the site $C_R$ closer in time. Moving $C_R$ closer in time lowers the appropriate discount factor and thus increases its present value cost. Diverting dredged material to some disposal alternative extends the life of the existing confined disposal facility and thus defers the cost of some new replacement disposal site. Thus deferral lowers the present value cost of acquiring the new site. The Turvey marginal cost approach to estimating changes in disposal costs is based largely on fundamental engineering economics.

Using marginal cost theory (or fundamental engineering economics) to measure the benefits and costs has also been employed directly for evaluating water conservation (Walski 1983; Lund 1987) and solid waste recycling (Lund 1990a) and indirectly, for measuring the benefits associated with pricing strategies (Turvey 1969, 1971).

## The Present Value Cost of Disposal

The present value cost of disposing of a fixed annual volume of dredged material is given by (1), assuming the existence of a single disposal site with a fixed volume capacity

$$PVC(Q_D) = \sum_{t=0}^{T} [c_D Q_D (1 + i)^{-t}] + C_R(1 + i)^{-T} + \sum_{t=T}^{\infty} [c_{2D} Q_D (1 + i)^{-t}] \quad \ldots\ldots (1)$$

Here $T$ = the time when the existing disposal site is filled, $c_D$ = the transportation and placement cost of a unit of dredged material, $Q_D$ = the annual rate of dredged material disposal, $i$ = the real discount rate, $C_R$ = the cost





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of closing and replacing the existing disposal site, and $c_{2D}$ = the transportation and placement cost for disposing of a unit of dredged material in the new disposal site. The new disposal site is assumed to be very large and capable of accommodating dredged material for a very long, approximately infinite, period of time. So long as the combined capacity of the present and next future disposal sites are very large, on the order of 60+ years, this is not a bad assumption and avoids the need to specify a long series of planned future disposal sites and their costs. This formulation is also appropriate if $C_R$ represents the cost, discounted to year $T$, of a series of future disposal sites that have a large combined capacity.

Another assumption in (1) is that transportation and placement costs of dredged material in the disposal site are linear. This may not be the case where there is a substantial elevation difference in the site over its remaining lifetime. A substantial elevation difference would typically imply the need for booster pumps to raise the sediment to the top of the site for disposal. These booster pumps add substantially to the cost of transportation and placement and this cost would increase with time. If booster pump or other such costs were expected to be important, they could be entered into (1) by allowing $c_D$ to vary with time or the amount of capacity remaining in the disposal site.

Eq. (1) can be simplified using fundamental engineering economic equations to:

$$PVC(Q_D) = c_D Q_D \frac{(1+i)^T - 1}{i(1+i)^T} + C_R(1+i)^{-T} + \frac{c_{2D}Q_D}{i}(1+i)^{-T} \qquad (2)$$

This result can also be expressed using continuously compounded interest rates, $r = \ln(1+i)$ (Theusen and Fabrycky 1984). This is a more convenient form that will be useful later

$$\mathrm{PCV}(Q_D) = c_D Q_D \frac{1 - e^{-rT}}{r} + C_R e^{-rT} + \frac{c_{2D}Q_D}{r} e^{-rT} \qquad (3)$$

The annualized cost of disposal under the circumstance of a long planning horizon is:

$$A = iPVC \qquad (4)$$

The time when the existing disposal site is filled is given by the time when accumulated disposal equals the site's present volume capacity:

$$T = \frac{V}{Q_D} \qquad (5)$$

where $V$ = the present empty volume remaining in the disposal site and $Q_D$ = the disposal site capacity filled each year.

The formulation of the aforementioned cost equations and mass balances provides a performance measure for testing the cost impact of various disposal designs.

## The Cost of Permanent Changes in Disposal Rate

In managing the dredged material disposal system it is often useful to evaluate the cost consequence of a proposed change in disposal rates. Such



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changes can result from diversion of some proportion of dredged material elsewhere (perhaps to wetland restoration projects) or any additional disposal required from expansion of nearby waterways.

For permanent changes in disposal rates, changes in disposal cost can be estimated using the aforementioned equations for the existing and proposed disposal rates, plus the addition of any costs for diverting dredged material to some alternative use. These are developed next for the case where disposal is accommodated by an existing dredged material disposal site with a limited volumetric capacity.

The present value cost resulting from a change in disposal rate, $\Delta Q$ is given by:

$$\Delta PVC = PVC(Q_D + \Delta Q) - PVC(Q_D) \quad (6)$$

This is expanded using (3) to yield

$$\Delta PVC(\Delta Q) = c_D(Q_D + \Delta Q)\frac{1 - e^{-r(T+\Delta T)}}{r} + C_R e^{-r(T+\Delta T)}$$

$$+ \frac{c_{2D}(Q_D + \Delta Q)}{r} e^{-r(T+\Delta T)} - \left(c_D Q_D \frac{1 - e^{-rT}}{r} + C_R e^{-rT} + \frac{c_{2D}Q_D}{r} e^{-rT}\right) \quad (7)$$

The change in the lifetime of the existing disposal site resulting from the permanent change in the disposal rate is $\Delta T$. This is given by:

$$\Delta T = T' - T \quad (8)$$

where $T'$ = the disposal site lifetime for the new disposal rate. This becomes

$$\Delta T = \frac{V}{Q_D + \Delta Q} - \frac{V}{Q_D} \quad (9)$$

or

$$\Delta T = \frac{V(Q_D - Q_D - \Delta Q)}{Q_D(Q_D - \Delta Q)} \quad (10)$$

and finally,

$$\Delta T = \frac{-\Delta Q}{Q_D + \Delta Q} T \quad (11)$$

An increase in disposal rates (positive $\Delta Q$) shortens the disposal site's lifetime (negative $\Delta T$).

Eq. (7) can be further simplified to

$$\Delta PVC(\Delta Q) = c_D \Delta Q \frac{1 - e^{-rT}}{r} + c_D(Q_D + \Delta Q)\frac{1 - e^{-r\Delta T}}{r} e^{-rT}$$

$$+ C_R(e^{-r\Delta T} - 1)e^{-rT} + \frac{c_{2D}}{r} e^{-rT}[(Q_D + \Delta Q)e^{-r\Delta T} - Q_D] \quad (12)$$

This can be further reduced to:

$$\Delta PVC(\Delta Q) = \Delta Q\left[\frac{c_D}{r} + \frac{c_{2D} - c_D}{r} e^{-r(T+\Delta T)}\right]$$



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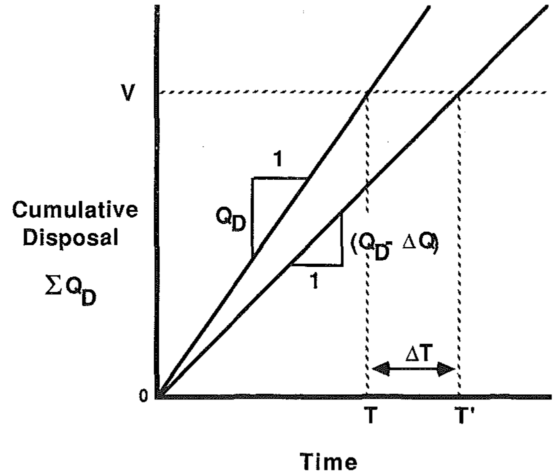


**FIG. 1. Effects of Continuous Diversions of Material on Lifetime of Dredged Material Disposal Site**

$$+ C_R(e^{-r\Delta T} - 1)e^{-rT} + Q_D \frac{c_{2D} - c_D}{r}(e^{-r\Delta T} - 1)e^{-rT} \quad (13)$$

The first term in (13) represents the present value cost savings resulting directly from changed disposal rates both before and after exhaustion of the existing disposal site. The second term represents the present value cost savings resulting from deferral (or acceleration) of disposal site closure and replacement costs. The third term represents present value cost savings resulting from deferral (or acceleration) of any increase in variable disposal costs, since the difference in variable unit costs has been deferred along with the exhaustion of the existing disposal site. These last two terms are combined in the final expression:

$$\Delta PVC(\Delta Q) = \Delta Q\left[\frac{c_D}{r} + \frac{c_{2D} - c_D}{r} e^{-r(T+\Delta T)}\right]$$

$$+ \left(C_R + Q_D \frac{c_{2D} - c_D}{r}\right)(e^{-r\Delta T} - 1)e^{-rT} \quad (14)$$

The value of $\Delta T$ is found using (11).

Two cases can be considered, permanently decreased disposal rates ($\Delta Q < 0$) and permanently increased disposal rates ($\Delta Q > 0$). The effects of permanent changes in disposal rate on a disposal site's lifetime are illustrated in Figs. 1 and 2 for decreases and increases in disposal rates, respectively. Permanent decreases in disposal rates could result from permanent diversion of some amount of dredged material produced annually to some alternative use or form of disposal or where there is some reduction in maintenance dredging. Permanent increases in the disposal rate for dredged material could result from expansion of a navigation project or the implementation of advance maintenance dredging under conditions where increases in mainte-

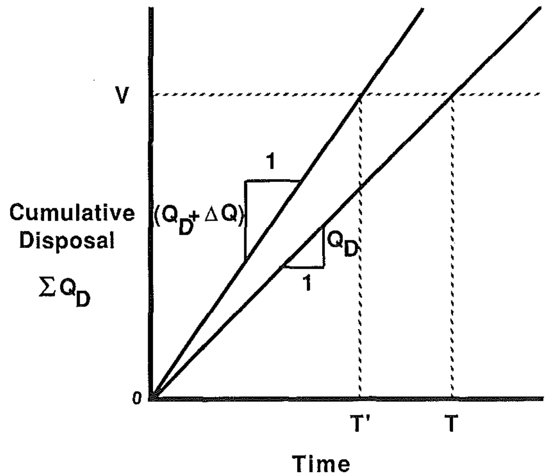


**FIG. 2. Effect of Increased Disposal Rates on Lifetime of Dredged Material Disposal Site**

nance dredging depths increase sedimentation rates. Note that for decreased disposal rates, $\Delta Q < 0$ and $\Delta T > 0$ and for increased disposal rates, $\Delta Q > 0$ and $\Delta T < 0$.

## Cost of a One-Year Change in Disposal Rate

Often, changes in disposal rates are temporary, where an opportunity exists for diverting some volume of material to some short-lived disposal alternative, such as the creation of a small wetland or a small land reclamation project using dredged material. After the diversion is completed, the disposal rate returns to its original amount. If the change is limited to the present year, the resulting change in disposal cost can be estimated using (15):

$$\Delta PVC(\Delta Q_0) = c_D Q_D \frac{1 - e^{-r(T+\Delta T')}}{r} + C_R e^{-r(T+\Delta T')} + \frac{c_{2D} Q_D}{r} e^{-r(T+\Delta T')}$$

$$+ c_D \Delta Q_0 - PVC(Q_D) \quad (15)$$

where $\Delta Q_0$ = the change in disposal rate during the present year. The change in disposal site lifetime $\Delta T'$ resulting from the temporary change in disposal rate is given by

$$\Delta T' = \frac{V - \Delta Q_0}{Q_D} - \frac{V}{Q_D} \quad (16)$$

which becomes

$$\Delta T' = -\frac{\Delta Q_0}{Q_D} \quad (17)$$

Using (3), (15) can be simplified to:



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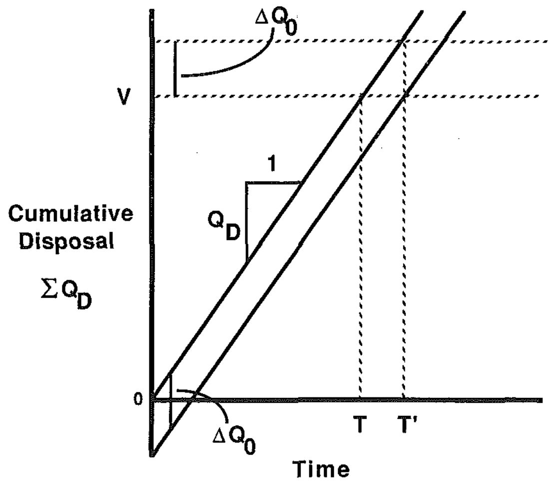


**FIG. 3. Effects of Single Diversion of Material on Lifetime of Dredged Material Disposal Site**

$$\Delta PVC(\Delta Q_0) = e^{-rT}\left(\frac{c_{2D} - c_D}{r} Q_D + C_R\right)(e^{-r\Delta T'} - 1) + c_D\Delta Q_0 \qquad (18)$$

or, substituting in the expression for $\Delta T'$

$$\Delta PVC(\Delta Q_0) = e^{-rT}\left(\frac{c_{2D} - c_D}{r} Q_D + C_R\right)\left(\frac{e^{r\Delta Q_0}}{Q_D} - 1\right) + c_D\Delta Q_0 \qquad (19)$$

For temporary changes in disposal rates, (19) summarizes changes in the costs of using the existing disposal site for both increases and decreases in the disposal rate. A complete economic evaluation of a diversion of dredged material to an alternative use would also have to include the costs of transporting and using the diverted dredged material in its alternative use. The change in disposal site lifetime is illustrated in Fig. 3.

The following section presents examples for the simple cases just described.

## Examples of Simple Cases

### Increased Disposal Rates

A small navigation project consists of a dredged channel and an existing upland disposal site. The project currently produces 50,000 cu yd of sediment annually for disposal. The existing disposal site has a capacity of 1,000,000 cu yd. The cost of replacing this site ($C_R$) is estimated at $8,000,000 in the year of replacement. A real discount rate ($r$) of 5% is assumed.

With a specified amount of expanded maintenance dredging, an additional 20,000 cu yd/year of sediment is estimated to be produced in the average year, for a total average annual disposal rate of 70,000 cu yd/year. This results from averaging disposal in years when dredging is performed with years when dredging is not performed. The cost of transporting and placing the additional material ($c_D$) is estimated at \$0.50/cu yd. The replacement disposal site is assumed to have the same transportation and placement cost ($c_D = c_{2D}$).

This increase in disposal rate decreases the lifetime of the existing disposal site from 20 years to 14.3 years. Therefore $\Delta T = -5.7$ years. This could be found using (11).

Applying (14), then, results in a total increase in disposal cost of \$1,170,000. The origins of this quantity can be explained as follows. The increased disposal cost due to expanded maintenance dredging is then the sum of the increased transportation and placement costs plus the increase in the present value of disposal site replacement costs. The increased transportation and placement costs come to \$0.50/cu yd · 20,000 cu yd/year = \$10,000/year. With a 5% discount rate and an infinite planning horizon, this additional transport and placement cost comes to a present value cost of \$200,000.

The increased present value cost of replacing the disposal site is its cost with additional disposal minus its cost without additional disposal. Without additional disposal, the existing site would be exhausted in 20 years ($T$). Increasing the disposal rate to 70,000 cu yd/year decreases this time to 14.3 years ($T'$). This increases the present value cost of replacing the disposal site by \$970,000. Note that for this example the increase in disposal site costs far outweighs the increase in disposal operations costs. The total increased disposal cost for this expanded maintenance dredging example is then \$1,170,000. This represents an annualized cost of roughly \$58,000.

In evaluating the total value of this expanded maintenance dredging, this increase in disposal cost would have to be subtracted from other net benefits resulting from expanded maintenance dredging.

**Decreased Disposal Rates**

Consider a small maintenance dredging project that produces 100,000 cu yd/year of material ($Q_D$). The cost of transporting and placing this material in an existing upland disposal site ($c_D$) is \$0.50/cu yd. The capacity of the existing site is 800,000 cu yd ($V$). When this site is exhausted, a new site must be acquired at a cost of \$5,000,000. The new disposal site has greater transportation and placement costs of \$0.75/cu yd ($c_{2D}$).

A disposal alternative is being considered that would divert 50,000 cu yd/year ($\Delta Q$) from the material stream to a nearby beach nourishment project. The net cost of this is \$0.70/cu yd. The real discount rate is assumed to be 5%.

The present value of net disposal benefits from implementing this alternative is given by (11) and (14). If this alternative were implemented, it would delay the filling of the existing disposal site from 8 to 16 years, or $\Delta T = 8$ years. This could be found using (11).

Assuming it is desirable to continue the disposal alternative after the closure of the existing site, (14) gives the present value cost of the alternative. In this case, the result is a net disposal benefit of \$1,827,000. These disposal benefits must be considered along with the cost of transporting and placing the diverted dredged material in its alternative use, any additional administrative or monitoring costs of diverting the material, and the direct beneficial use (or cost) of the alternative use of the material. Lund (1989a, 1989b) has more preliminary, but broader discussions regarding the integration of disposal costs with other costs and benefits of changes in disposal rates.

## A Method for Longer-Range Disposal Planning

Often, several alternatives to disposal are available over a moderately long-term planning horizon with a single disposal site and a costly replacement disposal site (or series of future disposal sites). The alternatives to disposal also come at some cost. The solution of this problem often centers largely on how the alternatives to disposal should be used in the short and intermediate terms to optimally defer the expense of new disposal sites.

A linear programming method is suggested for cases where a number of alternatives to disposal of dredged material are being considered to defer replacement disposal sites. The method employs a series of linear programs, one for each possible disposal site lifetime, to provide a least-cost schedule for a number of different alternatives to disposing dredged sediment in the existing traditional disposal site. The method is similar to that developed for least-cost scheduling and evaluation of solid waste recycling (Lund 1990a) and water conservation (Lund 1987). The formulation of the linear program is described below.

The present value cost of disposal and alternatives to disposal appear in the objective function next

$$\min \sum_{t=0}^{T} \left( c_D Q_{Dt} + \sum_{j=1}^{n} c_{Aj} Q_{jt} \right) (1 + i)^{-t} + C_R(T)(1 + i)^{-T} \quad \text{(20)}$$

where $T$ = the disposal site lifetime under consideration, $c_D$ = the unit cost of transportation and placing a unit of dredged material in the existing disposal site, $Q_{Dt}$ = the volume of dredged material disposed of in the existing disposal site in year $t$, $c_{Aj}$ = the average cost of disposing a unit of dredged material through disposal alternative $j$, $Q_{jt}$ = the volume of dredged material disposed of using alternative $j$ in year $t$, $i$ = the real discount rate, and $C_R(T)$ = the cost in year $T$ of closing and replacing the existing disposal site plus the present value in year $T$ of any increased unit disposal costs for future sites. Note that this formulation requires that disposal alternatives have insignificant fixed or start-up costs, or that these costs can be distributed proportionally to the use of a disposal alternative.

The minimization of this objective function is limited by the following constraints:

$$Q_{Dt} + \sum_{j=1}^{n} Q_{jt} \geq q \quad \text{for all } t \leq T \quad \text{(21)}$$

$$\sum_{\tau=0}^{t} c Q_{D\tau} \leq V \quad \text{for all } t \leq T \quad \text{(22)}$$

where $c$ = a compaction or bulking coefficient

$$Q_{jt} \leq q_j \quad \text{for all } t \leq T \quad \text{(23)}$$

for all disposal options $j$ with limits on their rate of utilization, and

$$\sum_{\tau=0}^{t} Q_{j\tau} \leq X_j \quad \text{for all } t \leq T \quad \text{(24)}$$

for all disposal options $j$ with total disposal volume limits.

The first constraint requires that the sum of traditional and alternative forms of material disposal equal the total amount of material dredged each year ($q$). There is one of these constraints for each year in the planning horizon.

The second constraint limits total disposal in the single disposal site over the planning horizon to the disposal capacity $V$. A compaction coefficient $c$ is included to allow for the effects of dewatering or net bulking of dredged material. If dewatering and consolidation occur rather quickly for the particular dredged material and site, $c$ will be a rather constant ultimate compaction ratio. However, if dewatering and consolidation are slow, additional constraints may be needed to limit the maximum disposal rate and accumulated disposal at each time, reflecting the different values of $c$ for each time when disposal is made ("Confined" 1987).

The third constraint limits the use of individual alternatives to conventional disposal in any given year. This would apply to alternatives with a limited "carrying capacity" that is expressed in terms of flow per year, $q_j$. For example, only a limited amount of dredged material would be useful as cover for nearby municipal solid waste landfills in each year.

The fourth constraint applies to disposal alternatives that have a limited capacity expressed in terms of volume over the planning horizon, $X_j$. For instance, the use of dredged material for a particular land reclamation project or the creation of a particular wetland area can only adsorb a limited amount of dredged material.

If some disposal alternatives are available only in the near future and cannot be held off indefinitely, this can be represented by only defining $Q_{it}$ for values of $t$ when alternative $j$ is available.

Solution of the aforementioned linear program for a given value of $T$ gives the least-cost schedule for employing disposal alternatives to reduce the cost of replacing an existing disposal site.

This linear program must be solved several times, for varying values of $T$, to find both the least-cost schedule of dredged material disposal options and the least-cost time of depletion $T$ of the existing disposal site. If $T_{max}$ = the longest possible disposal site lifetime, where all disposal alternatives are maximally used, and $T_{min}$ = the shortest possible disposal site lifetime, where no disposal alternatives are employed, then a maximum of $T_{max} - T_{min}$ linear programs must be solved to find the least-cost disposal plan. In most cases, many fewer linear programs will need to be solved. If there is no feasible solution to the formulated linear program, the value used for the disposal site lifetime $T$ must be reduced.

Engineers employing this method will note that there is considerable uncertainty in many of the cost and physical parameters. This will present a problem for any methodical approach to dredged material disposal design and planning. The linear programming method is especially useful in light of these uncertainties. Linear program solutions are relatively easy, requiring no more than a few minutes for solution of reasonably sized problems by desktop computers. Furthermore, the output from most linear program solution packages contains substantial amounts of sensitivity analysis regarding the sensitivity of the least-cost solution to variations in parameter values. This sensitivity analysis is described elsewhere for general linear program solutions (Dantzig 1963; Schrage 1986; Hillier and Lieberman 1986) and for similar solid waste disposal problems (Lund 1990a).

A few particular aspects of sensitivity analysis merit mention here. These are the values of the "shadow prices," Lagrange multipliers, or dual variables associated with the constraints. The value of the shadow prices from the first constraint (21) represents the change in the present value of disposal costs (the objective function) resulting from a unit change in the amount of material dredged in a given year. These estimates are accurate for small changes in dredging rates. For very simple problems with a single disposal alternative and a single disposal site, this result will approximate closely the result given in the previous sections using Turvey marginal costs.

The shadow price associated with the second constraint (22) represents the change in the present value cost of disposal associated with a unit increase in disposal capacity $V$. Where it is possible to change the management of the disposal site to increase its ultimate capacity by a small amount, this shadow price could be used to estimate the value of such management changes.

The shadow price associated with the third class of constraint (23) represents the change in the present value of disposal costs from a unit change of a disposal option's disposal rate in a single given year. Such information would be useful to evaluate the sensitivity of the solution to small errors in the estimated carrying capacities of disposal alternatives. A similar interpretation would apply for shadow prices associated with the fourth class of constraints (24), except that these carrying capacities are in terms of volumes instead of flows.

The ease of solving new linear programs and the relatively large amounts of sensitivity analysis that accompany linear program solution output allow the engineer or planner to investigate a wide variety of planning scenarios for feasibility and cost. Disposal options representing a wide array of environmental consequences can be investigated to determine their cost consequences, allowing a methodical trade-off of environmental and cost performance and relatively explicit consideration of the major sources of uncertainty in the disposal problem. The method is illustrated in the relatively simple example problem next.

## Illustrative Example

A hypothetical maintenance dredging project utilizing a single existing disposal site has several alternative use options for the dredged material and has selected a replacement disposal site. The project manager must decide when and how much of the alternative uses of dredged material are economically desirable and at what time the existing disposal site should be closed.

The project creates 500,000 cu yd/year of dredged material in the average year. The existing disposal site has a remaining capacity of 5,000,000 cu yd and it costs $0.75/cu yd to transport and place dredged material at this site. Once the existing disposal site is exhausted, a replacement disposal site has been found, with a very large capacity (>20,000,000 cu yd), but will require a cost of $40,000,000 to acquire and develop, including environmental mitigation costs, and its use will result in transportation and placement costs of $3.00/cu yd. The large capacity of the replacement disposal site allows us to assume an infinite planning horizon. In cases where a series of small replacement disposal sites is considered, these may be thought of for this analysis as a single large disposal site with a lumped (and dis-

**TABLE 1. Disposal and Use Options for Example Problem**

| Use (1) | Net unit operating cost ($/cu yd) (2) | Annual use limit (cu yd/year) (3) | Total capacity (cu yd) (4) |
|---|---|---|---|
| (*a*) Disposal Sites | | | |
| Existing site | $0.75/cu yd | None | 5,000,000 cu yd |
| Replacement site | $3.00/cu yd | None | >20,000,000 cu yd |
| (*b*) Alternative Uses | | | |
| Ocean disposal | $8/cu yd | 200,000 cu yd/year | None |
| Levee construction | $7/cu yd | None | 1,500,000 cu yd |
| Local fill | $5/cu yd | 50,000 cu yd/year | None |
| Wetlands creation | $3.50/cu yd | None | 2,000,000 cu yd |

counted) cost. Moreover, since the operating cost of the replacement disposal site is smaller than that of any alternative, the use of disposal alternatives would be discontinued after adoption of the new large disposal site (at least as an economic concern). These two observations allow us to simplify the combined capital cost ($40,000,000) and operating cost (a present value of approximately $30,000,000) of the new disposal site as roughly $70,000,000 in capital cost incurred when the new disposal site is brought on line. A 5% real continuous discount rate is assumed.

There are four alternative uses for dredged material: ocean disposal, levee construction, local fill, and wetlands creation. Each of these uses has different net unit costs, some uses have limitations on their annual utilization, and some uses have limitations on the total volume of material they can accept over time. These are described in Table 1. Ocean disposal is limited to 200,000 cu yd/year due to environmental concerns, with a unit cost of $8/cu yd. Levee construction will be completed with 1,500,000 cu yd of material, at a unit cost of $7/cu yd, including a reduction for the value of the material in this beneficial use. Local fill cannot use more than 50,000 cu yd of material each year for construction and landscaping and incurs a net unit cost of $5/cu yd. And wetlands creation incurs a unit cost of $3.50/cu yd, but can utilize no more than 2,000,000 cu yd over time. These costs and limitations are likely to vary considerably between actual maintenance dredging projects. The numbers chosen here were selected to be not unreasonable, in some sense, and to illustrate several potentially useful results from this type of analysis. In actual practice, project engineers would need to base estimates of these costs and limitations on local conditions.

These costs and limitations were formulated as a series of linear programs, as already outlined. Since even this small problem involved many decision variables and constraints, a FORTRAN program was developed that writes the objective function and constraints from entered parameters. The linear program statement is written to a file; this file is then used as input to the LINDO linear programming solution package (Schrage 1986), which provides the least-cost solution to each linear program and large amounts of sensitivity analysis. Each linear program solution gives a least-cost disposal and alternatives schedule for a given year in which the replacement disposal site is brought on line.



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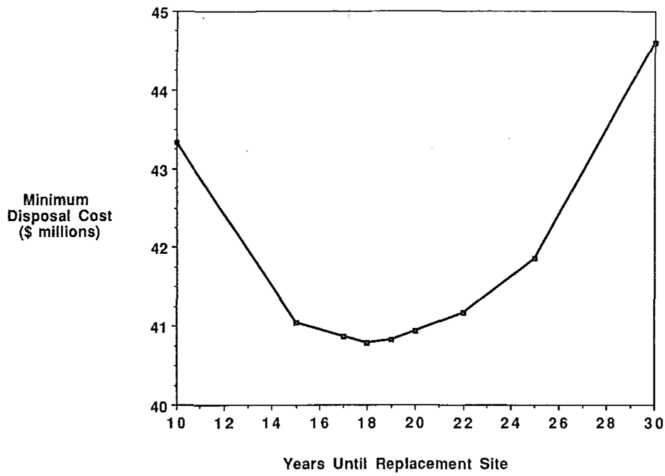


**FIG. 4. Minimum Disposal Costs for Different Times until Site Replacement**

If none of the alternatives to the existing disposal site are employed, the existing disposal site will be exhausted in year 10, and the replacement disposal site will be required in the same year. If all disposal alternatives are maximally used, the replacement disposal site can be delayed until year 31. The least-cost schedule falls somewhere in this 21-year range. Therefore, there are 21 possible linear programs.

The minimum disposal cost for each year in which the replacement disposal site can be brought on line is presented in Fig. 4, plotted from the results of nine linear programs. The least-cost time for the replacement disposal site is 18 years from the present. Note that there is little variation in total cost near the year 18 replacement site time. There is less than $250,000 difference between year 15 and year 18 costs, for example. Therefore, the selection of year 18 as the exact year for the replacement disposal site is not crucial. The total savings of the year 18 schedule over the do-nothing year 10 schedule is only $4.5 million, or about 10% of year 10's present value cost.

The least-cost schedule of disposal alternatives for this year 18 replacement horizon is given in Table 2. For this schedule, the existing disposal site is used exclusively for the first five years. This disposal option has the lowest unit cost by far of all the options. From year 6 until year 10, the bulk of material disposal is still sent to the existing disposal site, although the local fill option is also employed to its full, but relatively limited extent. In year 11, wetlands creation enters the schedule, accepting a limited amount of material, along with the local fill option and more limited disposal into the existing disposal site. The existing disposal site is filled at the end of year 11. From year 12 until year 15, local fill and wetlands creation accept all dredged material. At the end of year 15, the wetlands creation project is completed and can accept no more material. From year 16 until year 18, material is disposed of in local fill and levee construction. At the end of year 18, only 150,000 cu yd of capacity remain in the levee construction

TABLE 2. Least-Cost Disposal Schedule for Example Problem (cu yd)

| Year (1) | Existing disposal site (2) | Ocean disposal (3) | Levee construction (4) | Local fill (5) | Wetlands creation (6) |
|---|---|---|---|---|---|
| 1 | 500,000 | 0 | 0 | 0 | 0 |
| 2 | 500,000 | 0 | 0 | 0 | 0 |
| 3 | 500,000 | 0 | 0 | 0 | 0 |
| 4 | 500,000 | 0 | 0 | 0 | 0 |
| 5 | 500,000 | 0 | 0 | 0 | 0 |
| 6 | 450,000 | 0 | 0 | 50,000 | 0 |
| 7 | 450,000 | 0 | 0 | 50,000 | 0 |
| 8 | 450,000 | 0 | 0 | 50,000 | 0 |
| 9 | 450,000 | 0 | 0 | 50,000 | 0 |
| 10 | 450,000 | 0 | 0 | 50,000 | 0 |
| 11 | 250,000 | 0 | 0 | 50,000 | 200,000 |
| 12 | 0 | 0 | 0 | 50,000 | 450,000 |
| 13 | 0 | 0 | 0 | 50,000 | 450,000 |
| 14 | 0 | 0 | 0 | 50,000 | 450,000 |
| 15 | 0 | 0 | 0 | 50,000 | 450,000 |
| 16 | 0 | 0 | 450,000 | 50,000 | 0 |
| 17 | 0 | 0 | 450,000 | 50,000 | 0 |
| 18 | 0 | 0 | 450,000 | 50,000 | 0 |

option. After year 18, all dredged material is sent to the replacement disposal site constructed during year 18. Ocean disposal is never used; it is too expensive for even limited use.

These results raise several observations regarding the least-cost scheduling of disposal and disposal alternative options. First, and most obviously, the least expensive alternatives should typically be employed before more expensive disposal alternatives. Using the existing disposal site was by far the least expensive disposal option ($0.75/cu yd). This was followed by local fill and wetland creation ($3.50–5.00/cu yd) and finally levee construction ($7/cu yd). Ocean disposal ($8/cu yd) was too expensive to ever merit use for this example, even for deferring the large expense of the new disposal site.

Second, the presence of volume-capacity constraints on some disposal options can alter this simple order in the schedule. For example, the local fill option is more expensive than the wetland creation option, yet it is employed first. This occurs because the wetland creation option has a limited volume capacity, which is entirely used before the end of year 18. This raises the utility of employing the local fill option earlier to defer exhaustion of the existing disposal site until year 11. Local fill, a rate limited disposal option, is then employed until the end of year 18. These cost-reducing alterations in the ordering suggested in the first observation are not easily found by intuition, but are readily found by linear programming. Note that only one exhaustible disposal option is used at any one time, and that this is the least-cost exhaustible disposal option.

Third, the existing site might often be depleted well before the replacement disposal site is required. In this example, the existing site was filled in year 11 and the replacement site was needed for year 19. Disposal of





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material during the intermediate period exhausted the volume capacity limited wetlands creation and levee construction options. (However, sit acquisition uncertainties might encourage acquisition of replacement disposal sites as soon as possible, to ensure their availability when they are needed.)

The sensitivity analysis that accompanies the linear programming solution output is also informative. The shadow price (Lagrange multiplier or dual-price) for the constraint representing the existing disposal site's capacity indicates that if the capacity of that site could be expanded by a small amount, it would reduce the overall present value cost by $3.16/cu yd. In this case, increases in the site's capacity would allow lesser use of more expensive disposal options. Thus, if better compaction or small additions to the site expanded the site's capacity by 100,000 cu yd, the disposal managers should be willing to pay up to $316,000 in the present year for this increased capacity.

Similarly, the shadow price for the wetland's volume capacity constraint is $1.57, indicating that disposal manager should be willing to pay $1.57 in the present year to increase the disposal capacity for wetlands creation by 1 cu yd. Constraints on the rate at which local fill can absorb dredged material also have shadow prices, indicating the reduction in the present value of disposal costs with unit increases in the rate of local fill disposal in each year.

The effects of increases or decreases in the production of material requiring disposal can also be studied using shadow price values, since total disposal in each year is represented by a constraint. A small increase in dredged volume in year 10, to accomplish new work dredging for instance, would increase the present value of disposal cost by $3.68/cu yd of increased dredging.

Other items of sensitivity analysis can be used to study the effects of some other uncertainties in the problem. For instance, the reduced cost for ocean disposal in the last year is $0.41. This is the year in which this option would be most attractive. This means that if the coefficient of ocean disposal in the objective function for year 18 were reduced by $0.41, ocean disposal would become desirable in that year. Thus if the real cost of ocean disposal is reduced by $1.00/cu yd in the present (=$0.41 in year 18), ocean disposal will be utilized in year 18, and perhaps sooner. This makes sense in that reducing the cost of ocean disposal by $1.00/cu yd makes it comparable in cost to the levee construction option that is utilized.

The range analysis part of the linear programming solution's sensitivity analysis gives further cost-sensitivity information. For instance, if the cost coefficient in the linear program for local fill disposal in year 6 is increased by $0.01/cu yd, it will no longer be optimal to dispose by local fill in year 6. Certainly, some aspects of the solution are *very* sensitive to uncertainties in the problem's parameter values.

A final form of sensitivity analysis is to develop alternative cost and constraint scenarios and solve separate sets of linear programs for each scenario. This highly flexible form of sensitivity analysis is facilitated by the ease with which linear programs can be solved. The ability to reformulate and rerun linear programs can have an important role in assessing the cost of environmental limitations on disposal. For the particular aforementioned example, for instance, any removal of the ocean disposal option for environmental reasons would be economically insignificant, since it never entered the solution anyway. If levee construction with dredged material were eliminated for institutional or environmental reasons, however, a comparison of least-cost disposal schedules with and without the levee construction option would provide the cost of removing this disposal option.

Sensitivity analysis in linear programming is discussed more generally in Schrage (1986) and Hillier and Lieberman (1986) and for other volume limited disposal problems by Lund (1990a).

A major assumption in the aforementioned example is that the net operating cost of the replacement disposal site is less than the net operating cost of any of the alternative uses for dredged material. Were this not the case, i.e., the net operating costs of some of the alternative uses was lower than that of the replacement disposal site, then alternative uses with lower net operating costs should be used, reducing the disposal rates for the replacement site. In extreme cases, the economic adoption of alternative uses for dredged material might eliminate any need for replacement disposal sites.

## Conclusions

While environmental, political, and other engineering concerns often dictate the form and timing of disposal for dredged material, economics is often important as well. This paper has explored several relatively simple methods for evaluating the economics of disposal alternatives and increases in disposal rates and for the development of least-cost schedules for employment of various disposal alternatives. Some of these methods represent special cases of more general and complex approaches developed in the past.

Turvey marginal cost theory is employed for very simple cases where a single disposal alternative or an increase in disposal rates is to be evaluated. This marginal cost formulation is closely related to a fundamental engineering economic approach to the problem (Walski 1983).

A linear programming method is then proposed and illustrated for more integrated and least-cost scheduling of a variety of disposal options. This linear programming method is a special case of Ford's (1984, 1986) branch-and-bound solution method for more general disposal problems and requires that only one replacement disposal site be considered at a time and that the disposal alternatives have insignificant initial fixed costs.

The approaches taken here are short-cut forms of more rigorous integer-linear programming and related approaches to evaluate and plan dredged material disposal. While these simple methods will not be appropriate for all disposal problems, they should be of use for a significant number of somewhat simpler disposal problems where economics remains an important concern.

## Acknowledgments

Parts of this work were sponsored by the Dredging Research Program and the Investigation of Operations and Maintenance Techniques Program managed by the U.S. Army Waterways Experiment Station, Vicksburg, Mississippi with Tom Denes as project officer. Tom Denes also offered helpful comments on early versions of some of this work. The author also thanks Tom Wakeman, U.S. Army Engineer District, San Francisco, for his observations on the disposal problem and the wealth of data he provided as

background for this work. The misconceptions in this paper remain the writers own, however.

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## Appendix II. Notation

*The following symbols are used in this paper:*

$C_R$ = net cost of closing and replacing existing dredged material disposal site;

$c$ = compaction factor for disposal site;

$c_{Aj}$ = cost of transporting and placing unit volume of material in disposal alternative $j$;





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$c_D$ = cost of transporting and placing unit volume of material in disposal site;
$c_{2D}$ = cost of transporting and placing unit volume of material in replacement disposal facility;
$i$ = real annual discount rate;
$Q_D$ = initial disposal rate into disposal site;
$Q_{Dt}$ = volume of dredged material sent to disposal site in year $t$;
$Q_{jt}$ = volume of dredged material sent to alternative $j$ in year $t$;
$q$ = annual amount of material requiring disposal;
$q_j$ = flow capacity of disposal alternative $j$;
$r$ = real continuous discount rate;
$T$ = time of disposal site exhaustion for initial disposal rate;
$T'$ = time of disposal site exhaustion for new dispoal rate;
$T_{max}$ = maximum disposal site lifetime;
$T_{min}$ = minimum disposal site lifetime;
$t$ = time;
$V$ = initial volume capacity of dredged material disposal site;
$X_j$ = volume capacity of disposal alternative $j$ over planning horizon;
$\Delta Q$ = permanent change in volume rate of dredged material disposal;
$\Delta Q_0$ = temporary, one year change in volume rate of dredged material disposal;
$\Delta T$ = change in disposal site lifetime resulting from change in disposal rates;
$\Delta T'$ = change in disposal site lifetime resulting from one-year change in disposal rate; and
$\lambda_t$ = shadow price associated with disposal capacity constraint at time $t$.

## Appendix III. Conversion to SI Units

| To convert | To | Multiply by |
|---|---|---|
| cu yd | $m^3$ | 0.7646 |





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