ESTIMATION OF ENVIRONMENTAL RISK DUE TO POLLUTED SEDIMENT

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ABSTRACT

A method is presented to perform a risk-cost evaluation for sediment management applicable to the Danube Basin. Specifically, the environmental risk and the cost due to excavation and disposal of polluted sediment are evaluated and traded off in order to select sound management alternatives. Two main objectives of sediment management are considered: to minimize the cost of management and to minimize the environmental risk thereof. The economically optimal solution may not be realized due to the environmental risk involved. The environmental risk has several components such as human carcinogenic risk, human noncarcinogenic risk, and ecological risk related to a number of species. A trade-off analysis called composite programming is used: 1. to aggregate components of environmental risk considering different sources and compositions of polluted sediment in the river channel and/or reservoirs, 2. to find an alternative of sediment management which provides the best compromise between the cost and environmental risk involved.

KEYWORDS

Dredged material management; least-cost; environmental risk; human health; ecological risk; trade-off solution; composite programming.

INTRODUCTION

The purpose of this paper is to present a conceptual model for the risk-cost analysis of dredging and dredged material disposal. The risk-cost methodology aims at identifying viable alternatives for dredging and dredged material management by trading-off the cost and the environmental risk of the operation.

The system considered consists of several sites to be dredged and several disposal areas (either offshore or upland); several possible technological options for systems operation; the natural environment (human and non-human).

The objective of the systems operation is to excavate a prescribed amount of sediment at source areas and transport and dispose of it at disposal areas in an economic way but, at the same time, with an acceptable environmental risk. The environmental risk may have several components such as human carcinogenic and human noncarcinogenic as well as ecological risk related to several species.

From an engineering point of view, the most common approach has been to consider the system as an engineering-economic problem and find a minimum cost solution. Relatively, this is the simplest case and the problem can be solved using the principles of the classical transportation problem of operations research (de Neufville and Stafford, 1971). The transportation
problem is one in which multiple origins, destinations, transshipment points, pathways (roads, rail, waterways, etc.) and commodities exist, along with specified capacity constraints. The least costly (in time, money and distance) pathways are selected through a series of analytical relationships that specify the resources, objectives and constraints. There are several existing solutions of practical importance for this case. When a disposal failure event cannot be neglected, or the dredged material has no harmful pollutants, these solutions can be used to select the economically best systems. A model for this class of problems has been developed by Ford (1984).

Calculation of pollutant transport requires the numerical solution of the transport equations describing the pollutant movement in the media in question (ocean, groundwater, air). These solutions are difficult to combine with optimization methods such as the transportation problem mentioned. As a result, often a very simplified pollutant transport model is considered in conjunction with the cost minimization (e.g. Verdini and Leschine, 1985).

Most environmental risk problems have been specified as fixed constraints for the various pollutants at disposal areas. That is the allowable level of pollutants are prescribed to be not higher than given environmental standards. If these standards correctly reflect the actual environmental risk, this simplified constrained cost minimization method would lead to selection of a proper dredging and dredged material disposal system. However, incorrectly specified or excessively stringent constraints may lead to economically inferior systems.

The present model can be used to compare and evaluate alternative dredging and dredge disposal management options for four cases: least-cost solution without environmental constraints; least-cost solution with fixed environmental constraints; risk-cost analysis (or risk management); risk-cost analysis with consideration of the uncertainties inherent in the system.

ENGINEERING-ECONOMIC ANALYSIS

Maintenance of rivers and reservoirs requires excavation and disposal of the sediment deposited. Current practice is to excavate the material with a mechanical or hydraulic dredge and to transport it to disposal site(s) in barges or in hoppers on the dredge. In the system considered there are several sources of dredging material as well as several possible disposal sites:

- material source areas: 1, ..., L, and the total volume of sediment to be excavated from these areas \( b(1), \ldots, b(L) \).
- disposal areas: 1, ..., n, ..., N and the volume of sediment which can be disposed of at each area \( S_c(1), \ldots, S_c(n), \ldots, S_c(N) \).
- technological options: 1, ..., m, ..., M for excavation, transport and disposal.

Disposal areas may be divided into three groups: unconfined deep water (offshore) areas, near-shore areas, and upland areas. Offshore areas may be selected to minimize interference with human activities such as navigation. Nearshore areas are mostly contained natural or man-made ponding areas into which the dredged material is pumped or lifted. Upland areas may be existing solid or hazardous waste land fills. Technical aspects of dredging are described, among others, by Ford (1984) and in the Engineer Manual (1983).

The engineering-economic analysis defines the unknown amount \( x(l,n,m) \) of material dredged at source area \( l \) and transported between \( l \) and disposal area \( n \) and disposed at \( n \) using technology \( m \). This amount may change in different time periods, \( T \), say years and then it would be necessary to determine \( x(l,n,m) \) as a function of \( T \). The present approach does not consider the change in quantity of material transported in time.

Two material balance constraints are defined:

1. The total volume of sediment must be excavated at all areas and transported to disposal areas:

\[
\sum_{m=1}^{M} \sum_{n=1}^{N} x(l,n,m) = b(l) \quad (1)
\]

2. The total volume of material disposed at area \( n \) cannot exceed the capacity of the site \( S_c(n) \):
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\[ \sum_{m=1}^{M} \sum_{k=1}^{L} x(\xi, n, m) \leq Sc(n) \]  

(2)

Note that these constraints reflect the simplest case to facilitate the description of the conceptual model. Additional important factors such as volume reduction or material reuse can be incorporated into the model (Ford, 1984).

The total cost of systems operation can be defined with the help of unit cost \( g(\xi, n, m) \) as:

\[ C = \sum_{k=1}^{L} \sum_{n=1}^{N} \sum_{m=1}^{M} g(\xi, n, m) \cdot x(\xi, n, m) \]  

(3)

The economic objective is to minimize the total cost of systems operation: \( \min C \). If the economic optimization of the dredged material system operation would involve only the linear constraints (1,2) and a linear objective function (3), a linear programming algorithm can be used to determine the optimal dredging policy. If cost functions exhibit economy of scale, they become non-linear, then standard non-linear programming can be used.

The engineering-economic analysis may result in selecting the least-cost dredging management scheme. This scheme, however, may not be realized due to the ecological and human health risk involved.

HAZARD IDENTIFICATION

Hazard identification is the process of determining whether or not the exposure to an agent can cause an increase in the incidence of an adverse health or ecological effect. In the context of the present analysis, the particular hazards posed by individual chemical contaminants present in the dredged material should be identified. Toxicological hazards are defined by selecting contaminants of concern and constructing toxicity profiles for those contaminants. Another essential part of hazard identification refers to habitat disruption and loss of valuable (endangered, unique) species as a consequence of dredging or disposal even without toxicological hazards. This adverse ecological impact is measured by quantities such as acres of habitat disrupted or number of species lost.

Selection of contaminants for consideration in hazard assessment is based on the chemistry of dredged materials. Peddicord et al., (1986) lists appropriate documents and records to be checked for data on site contamination. The process involves four steps: a. List all identified contaminants in dredged material or at the dredging site; b. Document environmental concentrations of contaminants in dredged material or at the dredging site and determine representative values; c. Calculate rank score based on the method described in ICF (1985); d. Select chemicals of concern based on rank score. The rank score for each chemical is based on the product of the chemical concentration and a toxicity constant. The toxicity constant is derived from the minimum effective doses for chronic effects and a factor expressing the severity of the effect.

In some cases environmental standards are available to limit either the concentration or the total amount of chemical \( i \) disposed at a site. These standards may be incorporated as additional constraints into the engineering-economic model. A typical form of such a constraint is:

\[ \sum_{m=1}^{M} \sum_{k=1}^{L} x(\xi, n, m)CN_\xi(i) \leq V_n(i) \text{ for each disposal site, and contaminants } \]  

(4)

where \( CN_\xi(i) \) is the concentration of chemical \( i \) in the sediment at source area \( \xi \), and \( V_n(i) \) is the threshold volume of chemical \( i \) at disposal site \( n \).

Or the constraint can be expressed as concentration:

\[ \sum_{m=1}^{M} \sum_{k=1}^{L} x(\xi, n, m)CN_\xi(i) \leq \text{stand. } CN_n(i) \]  

(5)

where stand. \( CN_n(i) \) is threshold concentration at disposal site \( n \).
DOSE-RESPONSE ASSESSMENT

Dose-response assessment is the process of characterizing the relation between the exposure dose and the incidence of an adverse health or environmental effect in an exposed population. The dose-response relationship generally considers stochastic uncertainties involved and provides the probability of an adverse health or environmental effect as a consequence of a given exposure dose.

In dredged material management the types of adverse effects, A, can be divided into two groups: (a) Human Health: A₁, (b) Nonhuman Species: A₂. For human health, A₁, two broad categories of health effects are considered: (a) Carcinogenic effects: A₁₁, and (b) Noncarcinogenic effects: A₁₂. Within the group of nonhuman species effects A₂, the effects for selected species r may be considered: A₂₁,..., A₂r,...

The actual form of the dose-response relationships to be used in dredged material management depends on the effect considered. Namely,

A₁₁: Human Carcinogenic Effect.

\[ \text{Resp}_{1k}(A_{11}) = f_{1k}(C(i,k)) \]  

where: \( f_{1k} \) = the type of dose-response relationship for chemical i and exposure medium k, and 
\( C(i,k) \) = lifetime exposure dose of chemical i via medium k.

A possible unit for C(i,k) is mg of chemical i via medium k consumed by a human per day [mg·kg⁻¹·day⁻¹]. For example, the medium could be fish contaminated as a result of offshore disposal of polluted dredged material. Here a bioaccumulation test can be performed to estimate C(i,k), that is, the concentration of chemical i in fish.

A₁₂: Noncarcinogenic Effects.

Current methods for predicting human health effects from exposure to noncarcinogenic chemicals rely on the concept of an Acceptable Daily Intake (ADI), an average daily exposure that is considered safe or acceptable (EPA, 1980).

Because the slope of the dose response curve is not presently considered in deriving ADI’s, a formal, precise measure of the noncarcinogenic response is not available. Nevertheless an index of the noncarcinogenic response may be approximated as the ratio of the estimated exposure to the ADI as follows:

\[ \text{Resp}_{1k}(A_{12}) = \frac{C(i,k)}{\text{ADI}(i,k)} \]  

where: \( \text{Resp}_{1k}(A_{12}) \) = Hazard Index, or relative probability of a noncarcinogenic health effect from intake of chemical i from medium k, \( C(i,k) \) = lifetime exposure dose of chemical i from medium k [mg·kg⁻¹·day⁻¹].

A₂: Effects on Nonhuman Species.

\[ \text{Resp}_{2r}(A_{2r}) = f_r(\text{CO}) \]  

where: \( \text{Resp}_{2r} \) = measured in terms of organism mortality for species r rather than potentially sublethal responses such as cancer, \( \text{CO} \) = the concentration (or percentage) of polluted dredged material, and \( f_r \) = the type of dose-response relationship for species r.

Dose-response relationships for nonhuman species are based on:
- Sediment bioassay tests (Peddicord et al., 1985)
- Data on toxicity tests for individual contaminants, media, and species of concern.

EXPOSURE ASSESSMENT

Exposure assessment is the estimation of the magnitude, frequency, duration, and route of exposure. In dredged material management, components of exposure assessment include describing the following four elements: 1. environmental pathways and uptake routes for dredged material or
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chemical contaminants; 2. concentrations of dredged material or chemical contaminants in various media (water, sediments) in space and time; 3. exposed populations and resources; and 4. exposure dose (e.g., average rate of intake of a chemical contaminant by an individual of the exposed population). Each element should be considered at each disposal area for each type of adverse environmental effects. Bogardi et al. (1989) shows how exposure doses for these effects can be calculated. Accordingly, life-time exposure dose for both offshore and upland disposal areas can be expressed as:

\[ C_n(i,k) = \text{CONSTANT1}(n,i,k) \sum_{\ell} \text{CONSTANT2}(\ell) \cdot x(\ell,n) \]  

(9)

where \( \text{CONSTANT1}(n,i,k) \) and \( \text{CONSTANT2}(\ell) \) are defined in Bogardi et al. (1989).

RISK CHARACTERIZATION

In this step, results of exposure assessment and dose-response assessment are combined to estimate the extent of adverse effects associated with dredged material disposal. This extent of adverse effects is considered as the risk expressed as probabilities (carcinogenic risk and ecological risk) or some other indices (human non-carcinogenic risk).

Carcinogenic Risk, \( R_{11} \)

For a disposal site \( n \), the carcinogenic risk, \( R_{11}(n,i,k) \) can be calculated by substituting the exposure dose (Eq. 9) into the dose-response relationship \( f_{\ell,k} \) (Eq. 6).

\[ R_{11}(n,i,k) = f_{\ell,k} \left[ \text{CONSTANT1}(n,i,k) \sum_{\ell} \text{CONSTANT2}(\ell) \cdot x(\ell,n) \right] \]  

(10)

where: \( i = \) type of carcinogenic chemical and \( k = \) medium of exposure.

Then risk estimates \( R_{11}(n,i,k) \) can be summed over all media \( k \):

\[ R_{11}(n,i) = \sum_{k=1}^{K} f_{i,k} \left[ \text{CONSTANT1}(n,i,k) \sum_{\ell} \text{CONSTANT2}(\ell) \cdot x(\ell,n) \right] \]  

(11)

The total risk estimate at any area \( n \) can be estimated using methods of risk estimates for chemical mixtures (EPA, 1985). For example, if an additive model for chemicals is used—the simplest case—the total risk, \( R_{11}(n) \) can be taken as the sum across all chemicals:

\[ R_{11}(n) = \sum_{i=1}^{I} \sum_{k=1}^{K} f_{i,k} \left[ \text{CONSTANT1}(n,i,k) \sum_{\ell} \text{CONSTANT2}(\ell) \cdot x(\ell,n) \right] \]  

(12)

This risk estimate yields the probability that an individual will develop a cancer as a consequence of exposure stemming from site \( n \).

Human Non-Carcinogenic Risk, \( R_{12} \)

For disposal site \( n \), the human noncarcinogenic risk, \( R_{12}(n,i,k) \) can be calculated by combining Eqs. (7) and (9)

\[ R_{12}(n,i,k) = \frac{\text{CONSTANT1}(n,i,k) \sum_{\ell} \text{CONSTANT2}(\ell) \cdot x(\ell,n)}{\text{ADI}(i,k)} \]  

(13)

Similarly to the carcinogenic risk estimates for mixtures, the total risk \( R_{12}(n) \) can be expressed as

\[ R_{12}(n) = \sum_{i=1}^{I} \sum_{k=1}^{K} R_{12}(n,i,k) \]  

(14)

Note that \( R_{12}(n) \) is not expressed as a probability but as an index, called hazard index characterizing the relative magnitude of noncarcinogenic health hazard.

Ecological Risk, \( R_{2r} \)

The ecological risk for species \( r \) may be defined as mortality expressed as an expected value:

\[ R_{2r}(n) = N(n,r) \cdot A_n \cdot \frac{\text{OVERLAP}(n,r)}{A_n} \cdot \text{Resp}_{2r}(A_{2r}) \]  

(15)
where: \( N_z \) = the population density of species \( r \) over area \( n \), \( A_n = \text{magnitude of disposal area} n \) and \( \text{OVERLAP}(n,r) = \text{the overlap of the population area and the disposal area} \).

An estimate of risk, \( R_{2r}(n) \) can be obtained by substituting the dose-response relationship \( \text{ResP}^{2r} \) (Eq. 8) into Eq. 15.

The risk of habitat disruption or loss of valuable species may be an additional element of ecological risk. This risk can be expressed as an expected value for area of habitat disruption or number of species lost. Methods to estimate this element of ecological risk can be found in various reports of the Corps' Dredged Material Research Programs. The actual method of estimating habitat disruption risk results in an expression

\[
R_{2h}(n) = g \left( \sum_{r} x(0,n) \right)
\]

where \( R_{2h}(n) \) is the risk of habitat disruption or loss expressed in acres or number of species, and \( g \) reflects the method of estimation.

**RISK MANAGEMENT**

The purpose of risk management is to provide the Decision Maker with a scheme of dredged material management which results in the best trade-off between the cost of operation and environmental risk.

The present risk management procedure applies composite programming (Bardossy et al., 1987) consisting of a multi-level trade-off analysis.

Since the units of the risk and cost criteria are different (probability, index, mortality number, monetary value) the trade-off analysis requires that the actual values are normalized, that is, transformed into the interval 0 - 1. Using the maximum (worst) value of risk and cost and the minimum (ideal) value of risk and cost, the normalized value of a criterion can be expressed. For example, a normalized risk \( R_{\text{norm}}^{11} \) is

\[
R_{\text{norm}}^{11} = \frac{R^{11} - R_{11-}}{R_{11+} - R_{11-}}
\]

where \( R^{11} \) = carcinogenic risk and \( R_{11-} = \) the lowest risk (zero or background), \( R_{11+} = \) the highest risk pertaining to the least-cost solution of the dredged material management problem.

Similarly, normalized values for other types of risk and cost can be calculated.

**Level 1 analysis.** Normalized values of risks, \( R_{\text{norm}}^{11}(n) \), \( R_{\text{norm}}^{12}(n) \), \( R_{\text{norm}}^{2r}(n) \) are calculated as functions of the decision variable, \( x(\ell,n) \) using Eqs. 12, 14, 15, 16, and 17.

**Level 2 analysis.** Composite risk \( R_1 \) is calculated for human health risk from \( R_{\text{norm}}^{11} \) and \( R_{\text{norm}}^{12} \)

\[
R_1(n) = \left[ \alpha(11,n) R_{\text{norm}}^{11} + \alpha(12,n) R_{\text{norm}}^{12} \right]^{1/p_1}
\]

where \( \alpha(11,n) \), and \( \alpha(12,n) \) the weights expressing the relative importance for respcarcinogenic risk and non-carcinogenic risk at disposal area \( n \), and \( p_1 = \) balancing factor for elements of human risk.

Similarly, composite risk \( R_2 \) is calculated for ecological risk considering species \( 1, \ldots, r, \ldots \), and habitat disruption:

\[
R_2(n) = \left[ \sum_{r} \alpha(2r,n) R_{\text{norm}}^{2r}(n)^{p_2} \right]^{1/p_2}
\]

where \( \alpha(2r,n) \) = the weights expressing the relative importance among mortality risk for various species, \( r \), and habitat disruption at disposal area \( n \), and \( p_2 = \) the balancing factor for ecological risk.

**Level 3 analysis.** In this level, composite risk \( R(n) \) is calculated for each disposal area \( n \) from human health risk \( R_1(n) \) and ecological risk \( R_2(n) \):
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\[ R(n) = \left[ a(1,n)R_1(n)p^3 + a(2,n)R_2(n)p^3 \right]^{1/p^3} \]  \hspace{1cm} (20)

where \( a(1,n) \) and \( a(2,n) \) are the weights expressing the relative importance for human health risk and ecological risk at disposal area \( n \), and \( p^3 \) is the balancing factor for human health risk and ecological risk.

Level 4 analysis. In this level a composite environmental risk \( R \) is calculated for expressing the overall environmental risk due to dredged material management in the total system considered.

\[ R = \left[ \sum_{n=1}^{N} \alpha(n)R(n)pn \right]^{1/pn} \]  \hspace{1cm} (21)

where \( \alpha(n) \) is the weights expressing the relative significance of disposal areas from environmental risk aspect, and \( pn \) is the balancing factor for environmental risk among disposal areas \( n \). On the other hand, the cost \( COST \) of systems operation is also calculated (Eq. 3).

Systems evaluation. As a result of Level 4 analysis both an overall composite risk estimate \( R \) and an operation cost estimate \( COST \) are available in the function of the decision variables \( x(i,n) \). Normalized costs can be calculated using Eq. 17 with cost figures. Thus the required trade-off relationship between \( R(x(i,n)) \) and \( COST \) can be constructed as illustrated in Fig. 1 using 8 discrete alternatives of dredging alternatives \( x(i,n) \). If a dredged material management system is to be evaluated in order to select one "best" alternative of systems operation, then a function \( L(z) \) can be defined to measure the distance between the ideal point and points representing alternatives \( z \). Here the notation is used to indicate a discrete set of variables \( x(i,n) \). This distance can be expressed as

\[ L(z) = \left[ a_1 R^p + a_2 \text{normCOST}^p \right]^{1/p} \]  \hspace{1cm} (22)

where \( a_1 \) and \( a_2 \) are weights reflecting the relative importance of economics versus environmental risk, and \( p \) is the balancing factor for economics versus environment.

Note that the ideal value for cost represents the least-cost solution for a single optimization of the economic objective function (Eq. 3).

A best management alternative corresponds to the smallest distance: \( \min L(z) \). In Fig. 1 the best management alternative is \( z_0 \). Note that the minimization of Eq. 22 as an objective function includes Eqs. 17, 18, 19, 20, and 21.

Figure 1: Trade-off solution with composite programming.
CONCLUSIONS

1. The conceptual model has two main parts. One describes the engineering-economic aspects of the system, the other describes the environmental effects, expressed as risk, of dredged material management.

2. Though the principles and even the terminology for these two components have traditionally been quite different, the conceptual model endeavors to connect them in such a way that their original features are kept intact.

3. The approach does not seek to express components of environmental risk as monetary values. It is believed that it is often so arbitrary to assign monetary values for the quite different types of consequences (e.g. consequence of cancer, other health effects or expected mortality rate for several species) as to be meaningless. Rather, these components of environmental risk are considered according to their various common units, and an overall risk index is derived expressing the relative significance and biological nature of these components. Then, the trade-off relationship between the overall risk index and costs can be used to express the idea of the "willingness to pay for risk reduction".

4. It is believed that the proposed risk analysis method results in a simple and transparent final trade-off analysis (Fig. 1).

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