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RISK MANAGEMENT OF ACCIDENTAL WATER POLLUTION: AN ILLUSTRATIVE APPLICATION

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ABSTRACT

A general risk assessment and management approach is proposed for analyzing and controlling (accidental) environmental pollution events. This concept is illustrated by a simplified case study, describing hypothetic point-source toxic pollution of the river Danube and its effect on the downstream bank-filtered well system. The numerical example indicates the viability of the suggested approach, highlighting also the necessary information base of environmental risk studies.

KEYWORDS

Environmental hazards; risk management; river Danube; toxic pollution; illustrative case study.

INTRODUCTION

Recognizing, estimating and managing complex, synergistic and often irreversible processes of environmental degradation has become one of the most crucial issues of our era, cf. e.g. the monographs and surveys provided by Dorfman,Jacoby and Thomas,eds.(1972), Holling,ed.(1978), Loucks,Stedinger and Haith (1981), Haith (1982), Beck and van Straten, eds. (1983),WHO (1985), Somlyódy and van Straten, eds. (1986), Kleindorfer and Kunreuther,eds.(1987) or Richardson (1988). Many of the environmental hazards result from chemical accidents of different scale: a recent review of (Benedek,1988) summarizes the principal characteristics of those accidents along the river Danube. Without a reliable early warning system and proper emergency technologies, these accidents may endanger operating water works; this way, they might have serious health related consequences and significant cost implications.In addition,the construction of the Gabcikovo-Nagymaros barrage system also underlines the necessity of investigating safety measures to be taken.

Below an attempt will be made to demonstrate that the conceptual approach of risk analysis may contribute to "traditional" environmental management, specifically,to water pollution control. This is done via introducing a general framework for modelling environmental risks and applying it in a simplified case study. Throughout this paper a somewhat "technocratic" standpoint will be taken when concentrating on the modelling and numerical solution aspects; therefore important economic, social, political, jurisdictional etc. details are postponed to further, site-specific investigations.

RISK ASSESSMENT AND MANAGEMENT: PRINCIPLES, MODELS, SOLUTION METHODS

Basic notations and model forms

Many decision situations in technical design, economic planning and social sciences can be formally modelled by choosing a set of decision variables that meet a finite number of constraints (resource, logistical etc.) and perform optimally or acceptably under those given constraints. This problem has been the subject of optimisation theory/mathematical programming (MP) for some four decades. (For a recent survey, see e.g. Bachem, Grötschel and Korte, eds., 1983.) In spite of the variety of existing methods, there exist relatively few applications of MP in evaluating and managing environmental risks. This is probably due to several interconnected factors, viz.: difficulties of problem description, modelling, data collection and of choosing appropriate solution methods. Therefore, our aim below is to highlight MP models and techniques which can be applied for structuring and solving problems in environmental risk management.

Consider an environmental system S with components $c_1 \ldots c_N$ (for example - in water resources - flood control reservoirs, water supply networks, wastewater treatment plants, and their physical, economic, social environment may form the system S in question). Assume that the failure probability $p_n(x_n)$ of component c_n can be expressed as some function of a decision vector x_n $n=1,\ldots,N$. It is also assumed that the system S investigated has $k=1,\ldots,K$ accident scenarios, with consequences y_k and probabilities $P_k = P_k(x) = P_k(p_1(x_1) \ldots, p_N(x_N))$. The risk function associated to this problem-type is a function $R(x) = R(\{y_k(x), , P_k(x)\}\ k = 1,\ldots,K)$ which describes scenario probabilities and consequences as depending on the decision $x = \{x_n\}$.

In view of the ever-present scarcity of our resources, reasonable decision strategies may be sought, following e.g. one of the schemes below:

minimize {system design and operations costs, and resource demands}
{constraints on "acceptable" risks} (1)
{constraints on (the possible settings of) decision variables}

minimize {risk}
{constraints on available financial and other resources} (2)
{constraints on (the possible settings of) decision variables}

Subsequently we shall formalize these qualitative problem statements. It will be assumed that the risk-descriptor relationship can be given as a function $U(R(x))$ of the decision vector x, and that - beside the technical, economic etc. constraints - the total costs can also be expressed as a function $C=C(x)$. Then a simplified form of (1) can be given as: minimize $C(x)$, subject to

$$U(R(x)) \leq U_{max} \quad (U_{max} \text{ is the maximally acceptable utility (loss)}) \tag{3}$$

$$g_m(x) \leq 0 \quad m = 1,\ldots,M$$

Similarly, a possible symbolic formulation of (2) is

$$\text{minimize } U(R(x))$$

$$C(x) \leq C_{max} \quad (C_{max} \text{ is the admissible cost level}) \tag{4}$$

$$g_m(x) \leq 0 \quad m = 1,\ldots,M$$

Note here that both "U_{max}" and "C_{max}" may typically be vectors (expressing respectively the components of risk and resource bounds); further, $U(R(x))$ is often approximated in the (positive or negative sense) utility functional form (cf. e.g. Berger (1985) or French (1986))

$$U(R(x)) = \sum_k y_k(x)\ P_k(x) \quad \text{(expressing the "average (expected) risk")} \tag{5}$$

but this is neither essential nor always appropriate. Also note that although the above formulations suggest a (partial) discretization (viz. of probabilities and consequences of hazardous events), the possibility of analogous continuous problem descriptions is evident.

Stochastic model extensions

Although random factors of the above problem have been included to an extent by introducing component failure and scenario occurrence probabilities, it has been tacitly assumed that all relevant model parameters are known exactly. This assumption might be valid for "well-defined" technical systems, but is certainly not a priori valid in the context of environmental risk management: for example, the parameters y_k (consequences), p_n and P_k (probabilities) can frequently be regarded as partially unknown, uncertain or statistically fluctuating. In stochastic MP models this fact is taken into account explicitly, handling relevant model uncertainties as random variables (cf. e.g. Dempster, ed., 1980 or Wets, 1983).

Consider e.g. problem (3): if we accept that risks can be given only in a statistical sense, then (at least) the respective risk constraints are to be replaced by some statistically meaningful criteria. Examples are

{the constraints on acceptable risks are met on average}:

$$E\{U(R(x))\} \leqq U_{max} \tag{6}$$

{the probability of satisfying the risk constraints is "sufficiently near" to one}:

$$P\{U(R(x)) \leqq U_{max}\} \geqq 1 - \alpha \quad (0 < \alpha < 1 \quad \text{model parameter}) \tag{7}$$

{the extent of unfavourable deviations from "acceptable" risks is "sufficiently small", on average}:

$$E\{U(R(x));\ \text{on the condition that } U(R(x)) > U_{max}\} \leqq U_{max} + \beta \tag{8}$$

$(U_{max}, \beta > 0$ are model parameters)

Similarly, if total system costs and resource demands also vary, then objective functions of the type

$$\{\text{minimize expected total costs}\}: \quad \min E\{C(x)\} \tag{9}$$

{minimize a weighted combination of expectation and variance of costs}:

$$\min \alpha\, E\{C(x)\} + (1-\alpha)\, \mathrm{Var}\, \{C(x)\} \tag{10}$$

have a statistically well-defined interpretation.

Solution techniques

As noted earlier, there exists a large collection of MP methods, especially for solving deterministic (linear or convex and even small nonconvex) problems. Their direct use is, however, of limited value in the present context, because of the significant uncertainties involved: this indicates that deterministic modelling may serve here mainly for preliminary studies which are then to be followed by appropriate stochastic extensions.

It is evident (cf. e.g. the model "building blocks" (6)-(10)) that the stochastic reformulation of a basic deterministic model is far from being unambiguous and the model variants have, as a rule, markedly different statistical interpretation. Hence, it is a matter of careful judgement to select "appropriate" and numerically tractable model variants.

Referring briefly to numerical issues, it might be said that - depending on the model(s) chosen - solution methodology may vary considerably. In the case of stochastic modelling, one has to combine optimization techniques with methods of probability theory and statistics. Without going into details, one may list some of the most typical solution methods, viz:
- parametric scenario analysis;
- stochastic (Monte Carlo) simulation;
- deterministic approximations of stochastic models;
- direct combination of (deterministic or stochastic) optimization methodology with simulation techniques.

Concluding this brief methodological overview, it might be said that there is a spectrum of modelling and solution techniques which are applicable for handling complex problems in environmental risk analysis and management. In most cases, it might be very reasonable firstly to examine highly simplified models, in order to find an approximation of the main problem characteristics and the "promising" solution alternatives; this investigation can then be followed by a detailed study of a more specifically defined problem (and/or its corresponding subproblems). For different applications of the above principles, reference is made to the works cited in the Introduction and also to some of our recent investigations: Somlyódy and Pintér (1986), Cooke and Pintér (1987), Pintér and Somlyódy (1987) or Pintér (1987).

AN ILLUSTRATIVE CASE STUDY

All industries which use, consume and/or discharge in their production process hazardous (toxic, explosive, inflammable etc.) materials, can be considered as a potential danger to the environment. Our purpose below is to analyse water quality degradation, resulting water supply shortage and other damages (primarily: the financial consequences) which might be induced by an accidental point-source toxic pollution of river Danube. The industrial plant taken in our example is producing viscose fibres and other plastics; it has a list of stored raw materials and intermediates. We arbitrarily chose carbon disulfide (CDS) from this list, as it is stored in fairly large quantities which in case of a possible accident may escape together with the fire extinguishing agent through the drain network towards the Danube. (Note here that CDS is soluble in water to 2000 $mg \cdot \ell^{-1}$; furthermore, it will also react with diamines to form even more noxious compounds.) The industrial plant is situated in the impoundment section of the Nagymaros barrage and many water intake works (bank-filtered wells) might be endangered by the accidental CDS release. As seen from the above, we shall exclusively investigate here the short-term negative effects of a single polluting material. Furthermore - due to the lack of reliable data and related background information - simplifications and "educated guesses" will frequently be applied during the model formulation. In spite of the simplifications, we attempt to present an example which reflects realistic problem complexity and highlights the potentials of the systems analysis and optimization approach in risk management.

Scenario outline

Let us suppose that the following chain of events takes place:

i) Several storage tanks containing CDS fail by accident: as a consequence, CDS is discharged into the river in a (partially) uncontrollable manner.
ii) The CDS load disperses in the river: the spatial and temporal pattern of its distribution depends on the flux and on the actual river hydrologic/hydraulic characteristics.
iii) Given the CDS load and its distribution process, depending on the topographical location of the water supply works (bank well-systems), a number of these works may be forced to close. This action implies several adverse effects: water supply shortages or even possible toxic water supplies for a short period, and corresponding measures (resources/costs) for mitigating the risk: temporary water supply from emergency reserves, (extra) water treatment, rehabilitation of the well-system (and its filtration layer) or the eventual close-down of some irreversibly affected wells.

Quantitative analysis

Storage tank failure probabilities. The estimation of these is one of the crucial elements in the present study; however, data are scarce and failure rate estimates (from reference data sets or from expert opinions) might vary to a great extent, cf. the related discussions in Cohen (1984), Cooke et al. (1987), Kleindorfer and Kunreuther, eds. (1987) or Venuti et al. (1984). We shall choose here a simple model in which it is supposed that the subsequent tank failure times (i.e. the time period between two consecutive failure events) follow an exponential probability distribution function (p.d.f.) with known parameters a_n.Further,we assume that if tank n is found defective on a test, then its corresponding part (say, its valve) is immediately repaired or replaced. Supposing that the probability of a tank being operated is independent of the testing schedule, the probability of a failure (unavailability) on demand of tank n is expressed by

$$p_n(T_n) = \int_0^{T_n} (1-\exp(-a_n t))\, dt/T_n \approx a_n T_n/2 \qquad (a_n > 0) \tag{11}$$

where T_n denotes the testing (i.e. regular checking) interval for tank n. Now, it is supposed that one can control (to some extent) the unavailability of tanks by an appropriate choice of the testing intervals T_n. For simplicity, we may assume that the testing costs linearly depend on the test frequency, i.e. they are inversely proportional to the values T_n:

$$c_n(T_n) = C_n/T_n \qquad (C_n > 0 \text{ constant cost factors}) \tag{12}$$

Coupling the simple relations (11)-(12), we can approximate the maintenance/testing costs as a function of the corresponding failure probability:

$$c_n(p_n) \approx c_n\, a_n/(2\, p_n) \tag{13}$$

Note, that this simple model will allow us to "optimize" the choice of testing schedule, as all possible consequences studied below are explicitly dependent on the failure probabilities. In the lack of a similar description, one is confined to a "pure" scenario analysis which *per se* does not allow one to consider "optimized" actions.

Below we shall apply an additional simplification, by which the same testing schedule (t) and the same failure rates (a) are taken for all (n=1,...4) tanks. Denote the number of tanks failing during any time period T by $P_k(T)$ k = 0,1,...4. At this point, we shall take into account the "domino-effect", quite typical in the accident-type analysed: if it is strong, then $P_k(T) \approx P_1(T)$ k = 2,3,4. Consequently, it can be modelled e.g. in the following simple way (cf.(11)):

$$P_1(T) = a\, t/2; \quad P_{k+1}(T) = P_k(T)\, q_k \qquad k = 1,2,3 \tag{14}$$

(here the factors q_k are near to 1, reflecting the strength of the "domino-effect"). Note that the discrete probability distribution $\{P_k(T)\}$ is an explicit function of the time-horizon considered: for simplicity, we shall suppress T (assuming a prefixed horizon, say, a year) and the notation P_k will occasionally stand for $P_k(T)$.

The amount and rate of toxic discharge. Tank failures may result in an uncontrollable toxic load entering the river via the internal drains of the factory -supposing that appropriate control can not be obtained. (We shall not investigate here the possibility of in-plant emergency measures.) For illustrative purposes, the following simple model is applied: all tanks have the same capacity V_{max} = 37.5 t; further, if a tank discharges its actual content, then this (random) content V - for each tank independently - can be approximated by a corresponding (truncated) normal distribution with mean value E(V) = = $V_{max}/2$ = 18.75 and standard deviation D(V) = 7.30. (Note that the interval (0,37.5) covers, with probability 0.99 , the range of the normal variate N (18.75,7.30).) From the above assumptions it also follows that in case of simultaneous accidents of several tanks, the summed accidental discharge from k tanks is also normally distributed with mean value k E(V) and standard deviation $\sqrt{k}$ D(V). A similar model may describe the discharge time: it is supposed that the toxic pollutant load leaves the factory in a uniform rate during a time period which follows (truncated) normal p.d.f. with mean value 6.50 hr and standard deviation 2.17 hr. (Again, this implies that the interval (1,12) covers, by a good approximation, the range of the variate N(6.50,2.17).) From the above assumptions it follows that the primary pollution process, modelled by a flux of (randomly realized) intensity i, equals:

$$i = \{\text{total pollution load}\} / \{\text{discharge time}\} = TPL/DT \quad (kg \cdot s^{-1}) \tag{15}$$

where both TPL and DT are respectively parameterized normal variates.

Pollutant dispersion in the river. As seen from the above, the pollution load is influenced by a number of random (accidental) circumstances; further significant uncertainties originate from the actual hydrologic and hydraulic conditions of the river. The mixing of (point source) pollutants with the bulk of water in a stream can be described by the general transport equation

$$\frac{\partial c}{\partial t} + \frac{\partial}{\partial x}(v_x c) + \frac{\partial}{\partial y}(v_y c) + \frac{\partial}{\partial z}(v_z c) = \frac{\partial}{\partial x}\left(D_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z \frac{\partial c}{\partial z}\right) \qquad (16)$$

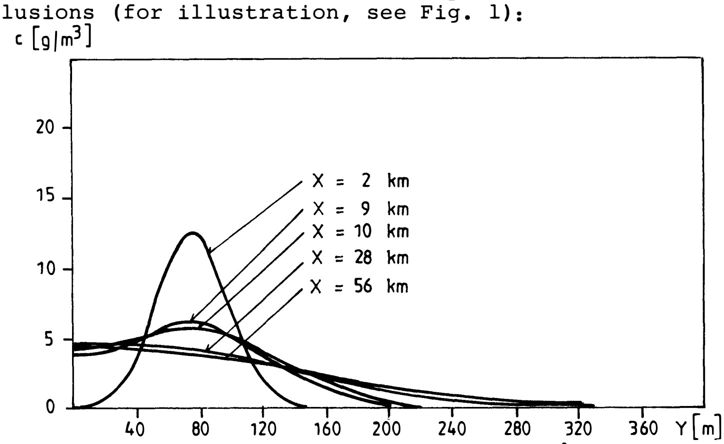
where t denotes time (s); x,y and z are the axes of the coordinate system in which the pollution dispersion process is described (the movement of the pollution flux is measured in meters, m); $c\,(\mathrm{kg \cdot m^{-3}})$ is concentration of the pollutant; v_x, v_y and v_z $(\mathrm{m \cdot s^{-1}})$ are coordinate-wise velocities of the river; finally, D_x, D_y and D_z $(\mathrm{m^2 s^{-1}})$ are diffusion coefficients.

The general (three-dimensional) form of equation (16) usually has to be simplified, in order to obtain data-supported and numerically tractable specifications. The special form of Eq. (16) applied here is derived via integrating it with respect to water depth (h, m): this leads to the equation of turbulent dispersion:

$$\frac{\partial}{\partial t}(h\bar{c}) + \frac{\partial}{\partial x}(h\bar{v}_x\bar{c}) + \frac{\partial}{\partial y}(h\bar{v}_y\bar{c}) = \frac{\partial}{\partial x}\left(hD_x^* \frac{\partial \bar{c}}{\partial x}\right) + \frac{\partial}{\partial y}\left(hD_y^* \frac{\partial \bar{c}}{\partial y}\right) \qquad (17)$$

In Eq.(17) depth-wise average values of the earlier introduced quantitites v and c are given; further, the notations D_x^* and D_y^* stand for the respective dispersion coefficients (see Somlyódy (1985) for more details).

On the basis of this description, numerical integration of Eq.(17) was accomplished under various initial conditions (viz., pollution intensity $(\mathrm{kg \cdot s^{-1}})$, streamflow rate $(\mathrm{m^3 \cdot s^{-1}})$, respective water depth h (m), velocity v_x $(\mathrm{m \cdot s^{-1}})$, $v_y \approx 0$ $(\mathrm{m \cdot s^{-1}})$ and corresponding dispersion coefficients $D_x\,(\mathrm{m^2 . s^{-1}})$, D_y $(\mathrm{m^2 \cdot s^{-1}})$). The results of our (off-line) numerical study served as a base for the following conclusions (for illustration, see Fig. 1):



x (m)	c_{max} $(\mathrm{g/m^3})$
2000	12.648
9000	6.017
10000	5.738
28000	4.585
31000	4.525
37000	4.385
42000	4.263
47000	4.142
56000	3.939

Fig. 1. Longitudinal (X) and cross-sectional (Y) evolution of c_{max}

i) The pollution process is properly characterized by the resulting maximal pollution concentration c_{max}.
ii) c_{max} is a monotonously decreasing function of the distance between the pollution discharge and the observation point: the form of this function can be numerically approximated.
iii) c_{max} is, to a reasonable approximation, linearly proportional to the pollution intensity and inversely proportional to the actual streamflow rate. Further, its value is only slightly dependent on the pollution load duration (on the time range (1 hr, 12 hr) investigated here).
iv) Large-scale engineering construction works may affect significantly the quantitative characteristics of the analysis above. For example, side effects of the Gabcikovo-Nagymaros barrage system (GNV) include the following (as estimated from our off-line numerical model):

- the dispersion coefficient D_y is decreased by more than an order of magnitude;
- the average velocity of water v_x is decreased by a factor of four;
- the (average) water depth may grow significantly;
- the overflow above the barrage increases volatilization.

Consequently, it can be expected that the duration of pollution events (upstream of GNV) increases, their intensity decreases and complete mixing (with enhanced stripping) takes place when passing over the barrage: hence, this construction will have an estimated overall positive effect on the pollution process characteristics.

The findings listed allow for the numerical generation of c_{max}; that is, for a concrete pollution event and corresponding river state,the concentration maximum value can be numerically traced to a reasonable distance (up to several ten kilometers); this, in its turn makes it possible to analyse the accident consequences, with respect to the downstream water works.

Pollution transport in the filtration zone. Before the effect of pollution on the quality of water pumped from the wells is investigated, the transport processes through the bank filter layers will be highlighted. In the present paper, there is no space to go into details of the transport phenomenon of physical and biogeochemical character, thus we make the following simplifying assumptions:
i) the river bed has no significant bottom sediment (that could be organically polluted) above the sandy gravel strata;
ii) for the sake of safety, no transformation (adsorption) of CDS is supposed during its travel through the filter layer to the wells; at the section of the wells complete dissolution can be duly supposed;
iii) on the basis of experience (gained from observations), one can estimate that in case of horizontal wells approximately 2 days and in case of vertical wells some 4 days travelling time can be expected in the filter layers.

Note here that in the future much more precise site-specific information should be collected; lacking such information, we shall confine ourselves below to a tentative analysis of the consequences of an accidental water pollution event.

Pollution effects and consequences. The calculations outlined yield maximum CDS concentrations which affect the water supply well-system: viz., if the (site--dependent) value c_{max} exceeds some threshold value, then the wells in question have to be closed down. In other words, given an accidental CDS load, the estimation of its distribution process leads in a straightforward manner to i) early warning of those water supply works which are potentially affected to a harmful extent, and to ii) corresponding risk mitigation actions.

In our example, only the cost implications of accidental pollution will be considered, i.e. health effects will not be directly included; this way, with a (random) accident scenario a corresponding summed monetary loss can be associated. Further, the risk of a particular maintenance policy will be defined as the expected (average) total loss which might be anticipated ("in the long run" taking, say, a period of several years):

$$R = R(t,P,L) = \sum_k P_k \, E(L_k) \qquad P_k = P_k(t) \qquad L_k = L_k(t) \tag{18}$$

where t symbolizes the operations policy (in our simple example, the testing interval is the sole decision variable) P represents the aggregated statistical model of the accident occurrences and L represents the consequences. Eq. (18) shows the expected value of losses, as a function of the accident probabilities and consequences indexed by the values $\{k\}$.

Let us consider now the cost factors. For simplicity, it is assumed that the operating policy costs depend on t according to (cf. (13))

$$c(t) = C/t \qquad \text{(C being some positive constant)} \tag{19}$$

Further on, we shall define total damage as the sum of close-down costs (CDC) and rehabilitation costs (RC) per water work affected. These will be given by

$$\text{CDC} = \{\text{No. of close-down days}\}\cdot\{\text{50 per cent daily water supply rate}\}\cdot\{\text{unit cost of emergency water supply}\} \tag{20}$$

$$\text{RC} = \{\text{No. of pollution travel days}\}\cdot\{\text{daily amount of safety water recharge needed}\}\cdot\{\text{unit cost of water recharge (flushing of wells)}\} \tag{21}$$

Note that fixed costs of a (preselected) early warning system or (stand-by) emergency technologies will not be subject to optimization here (as these are unavoidable safety measures). Consequently, in our greatly simplified example only the testing interval will be chosen according to the optimization model below.

$$\min\ C/t + \sum_k P_k\, E(\text{CDC}_k + \text{RC}_k) \qquad P_k = P_k(t) \qquad T_{min} \leq t \leq T_{max} \tag{22}$$

For example, let us take the following numerical data and ("domino effect" type) accident occurrence model:

<u>failure rate:</u> $a = 0.002$/yr;

<u>testing interval range:</u> $T_{min} = 1$ day ≈ 0.00274 yr; $T_{max} = 1$ yr;

<u>accident occurrence model:</u> $P_1(t) = a\,t/2 \quad P_{k+1}(t) = P_k(t)\,q_k \quad k = 1,2,3;$

$q_1 = 0.8 \quad q_2 = 0.9 \quad q_3 = 0.95;$

<u>testing procedure costs:</u> 0.01/test (in million Fts; 1 US $ ≈ 50 Fts);

<u>accident costs per affected water works:</u>

water work no.	distance from pollution discharge (in kms)	total costs of possible accident (CDC+RC, in million Fts)
1	2	19.2
2	9	68.3
3	10	10.7
4	28	1.0
5	31	3.3
6	37	4.3
7	42	2.6
8	47	78.4
9	50	23.3
10	56	21.3
11	56	53.3
12	56	78.4
13	61	1.3
14	64	49.5
15	60	9.2
16	64	29.1
17	68	20.3

Taking $t = T_{min}$, the estimated objective function value in (22) equals

$$3.65 + (2.74\cdot 98.2 + 2.19\cdot 102.5 + 1.97\cdot 106.8 + 1.87\cdot 473.5)\cdot 10^{-6} \approx 3.652 \text{ mFt/yr}$$

(Note that in this simplified example we assume that if a single storage tank fails, then only the first three water works are affected, while in case of 2,3 or 4 tanks failure the first five, six or all works are respectively affected, i.e. shut down). This result shows that testing costs are predominant: viz., "very frequent testing is too costly". Take now at the other extreme $t = T_{max}$, then (under the same assumptions) the estimated costs are

$$0.01+(1\cdot 98.2+0.8\cdot 102.5+0.72\cdot 106.8+0.684\cdot 473.5)\cdot 10^{-3} \approx 0.591 \text{ mFt/yr}$$

Note that in this case the expected damage costs are predominant: "too infrequent testing might prove dangerous". Taking now, say, $t = 0.25$ yr, one obtains the expected total costs and damages

$$0.04+(2.5\cdot 98.2+2\cdot 102.5+1.8\cdot 106.8+1.71\cdot 473.5)\cdot 10^{-4} \approx 0.185 \text{ mFt/yr}$$

Hence, the last testing policy seems definitely better than those two chosen previously. This indicates that, even elementary optimization concepts may yield more "promising" operating policies than those obtainable by "pure administrative regulations". By simple univariate optimization one can obtain in a few iterations that the "best" maintenance policy results taking $t \approx 0.13$ (i.e. some 7.69 tests/year), with an expected approximate cost (testing and possible damages) of 0.152 mFt/yr.

Concluding this paper, let us recall that in the illustrative example above, a number of greatly simplifying assumptions were made. In reality, a much more precise description would be necessary when e.g. expected damages are calculated: one has to consider a proper statistical description of the actual storage tank contents, a detailed analysis of the in-factory emergency actions and their possible results. Further, a statistical investigation of the environmental conditions is felt desirable: this has to include a streamflow-pollution dispersion study, proper account of the infiltration process and a detailed analysis of the emergency actions at the water works. This way, a sound risk assessment can be provided which, in its turn, makes it possible to elaborate on efficient management policies.

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REFERENCES

Bachem, A. Grötschel, M. and Korte, B., eds. (1983). Mathematical Programming: The State of the Art. Springer-Verlag, Berlin-Heidelberg-New York.

Back, M.B. and van Straten, G. eds. (1983). Uncertainty and Forecasting in Water Quality. Springer-Verlag, Berlin-Heidelberg-New-York.

Benedek, P. (1988). River Danube pollution and its risk assessment. In: Risk Assessment of Chemicals in the Environment. Richardson, M.L., ed. The Royal Society of Chemistry, London.

Berger, J.O. (1985). Statistical Decision Theory and Bayesian Analysis. Springer-Verlag,Berlin-Heidelberg-New York-Tokyo.

Cohen, A.V. (1984). Overview and definition of risk: its assessment and management. Environment International 10, 359-366.

Cooke, R.M., Goossens, L.H.J., Hale, A.R. and van der Horst, J. (1987). Accident Sequence Precursor Methodology. Research Report, Delft University of Technology, Delft; 122 pp.

Cooke, R.M. and Pintér, J. (1987). Mathematical programming in risk management. Research Report, Delft University of Technology, Delft; 16 pp.

Dempster, M.A.H., ed. (1980). Stochastic Programming. Academic Press, London.

Dorfman, R., Jacoby, H.D. and Thomas, H.A., eds. (1972). Models for Managing Regional Water Quality. Harvard University Press, Cambridge.

French, S. (1986). Decision Theory: An Introduction to the Mathematics of Rationality. Ellis Horwood, Chichester.

Haith, D.A. (1982). Environmental Systems Optimization. John Wiley and Sons, New York.
Holling, C.S., ed. (1978). Adaptive Environmental Assessment and Management. IIASA - Wiley Interscience, Chichester-New York-Brisbane-Toronto.
Kleindorfer,P.R. and Kunreuther,H.C., eds. (1987). Insuring and Managing Hazardous Risks:From Seveso to Bhopal and Beyond. Springer-Verlag, Berlin--Heidelberg-New York.
Loucks, D.P,, Stedinger, J.R. and Haith, D.A. (1981). Water Resources Systems Planning and Analysis. Prentice-Hall, Englewood Cliffs, New Jersey.
Pintér, J. (1987). A conceptual optimization framework for regional acidification control. Systems Analysis, Modelling and Simulation 4, 213-226.
Pintér, J. and Somlyódy, L. (1987). Optimization of regional water quality monitoring strategies. Water Science and Technology 19(5/6) 721-727.
Richardson, M.L., ed. (1988). Risk Assessment of Chemicals in the Environment. The Royal Society of Chemistry, London.
Somlyódy, L. and Pintér, J. (1986). Water quality management: methodology and applications. Foundations of Control Engineering 11, 177-189.
Somlyódy, L. (1985). Mixing of pollutants in rivers. (In Hungarian.) Vizügyi Közlemények 67, 185-202.
Somlyódy, L. and van Straten, G. eds. (1986). Modeling and Managing Shallow Lake Eutrophication. Springer-Verlag, Berlin-Heidelberg-New York.
Venuti, G.C. et al. (1984). Management of risks in the chemical and nuclear areas. Environment International 10, 475-482.
WHO (1985). European Regional Programme on Chemical Safety: Risk Management in Chemical Safety. (Extended report on a consultation, held in Ulm (FRG), 8-10 November 1984.)
Wets, R. (1983). Stochastic programming: Solution techniques and approximation schemes. In: Mathematical Programming: The State of the Art, Bachem, A., Grötschel, M. and Korte, B., eds. Springer-Verlag, Berlin-Heidelberg-New--York.