RISK MINIMIZATION MODEL FOR RIVER WATER QUALITY MANAGEMENT

Subimal Ghosh and P. P. Mujumdar

Indian Institute of Science, Bangalore-560012, India, E-mail: pradeep@civil.iisc.ernet.in

ABSTRACT

Methodology for minimization of risk in a river water quality management problem is presented. The risk minimization model is developed to minimize the fuzzy risk of low water quality along a river in the face of conflict among various stakeholders. The model consists of three parts: a water quality simulation model, a risk evaluation model with uncertainty analysis, and an optimization model. Fuzzy multiobjective programming is used to develop the multiobjective model. Probabilistic Global Search Lausanne, a global search algorithm, is used for the non-linear optimization. The result of the model is compared with the result of FWLAM, when the methodology is applied to the case study of Tunga-Bhadra River in southern India.

INTRODUCTION

Waste load allocation (WLA) in streams refers to the determination of required pollutant treatment level at a set of point sources of pollution to ensure that an acceptable level of water quality is maintained throughout the stream. Multiobjective problem solving technique in water resources was introduced by Monarchi et al. [1], which allowed the decision maker to trade off one objective versus another in an interactive manner. Tung and Hathhorn [2] reveal that fuzzy optimization is a valuable tool for solving the multi-objective water quality management problems. Sasikumar and Mujumdar [3] have formulated Fuzzy Waste Load Allocation Model (FWLAM) to demonstrate the application of fuzzy decision making in water quality management of a river system. Mujumdar and Subbarao [4] used genetic algorithms to solve FWLAM using QUAL2E.

A methodology for evaluation the fuzzy risk of low water quality was presented by Subbarao et al. [5]. Starting with that methodology, the present model is developed to minimize the fuzzy risk of low water quality. It consists of three parts: (i) water quality simulation model; (ii) evaluation of fuzzy risk; (iii) optimization model to minimize the risk. A backward finite difference formulation is used for water quality simulation model. Non-linear optimization model is solved by Probabilistic Global Search Lausanne (PGSL), a direct stochastic algorithm for global search, developed by Raphael and Smith [6].

RISK MINIMIZATION MODEL

Uncertainties due to both randomness and imprecision in a water quality management problem are considered in developing the risk minimization model. Water quality at a location in a stream
depends on the variability of different input parameters (e.g. temperature, streamflow, upstream water quality etc.). In FWLAM, developed earlier, such variability is not considered, as it is a deterministic model. Risk minimization model, developed in this paper, has two parts, deterministic and stochastic. The deterministic part maximizes the minimum acceptability level of FWLAM for mean condition of the input parameters. The stochastic part minimizes the fuzzy risk of low water quality, incorporating both kind of uncertainties in the optimization model.

**Fuzzy Waste Load Allocation Model**

The fuzzy waste load allocation model (FWLAM) developed by Sasikumar and Mujumdar [3] forms the basis for the optimization models developed in this paper. The FWLAM is described using a general river system. The river consists of a set of dischargers who are allowed to release pollutants into the river after removing some fraction of the pollutants. The goal of the Pollution Control Agency (PCA) is to improve the water quality and those of dischargers are to minimize the fractional removal levels and they are in conflict with each other. These goals are treated as fuzzy events and modeled using appropriate fuzzy membership functions. In the FWLAM, the following fuzzy optimization problem is formulated to take into account the fuzzy goals of the PCA and dischargers.

Maximize \( \lambda \) 

subject to

\[
\left[ \frac{c_{il} - c_{il}^L}{c_{il}^L - c_{il}^U} \right]^{x_{il}} \geq \lambda \quad \forall \ i, l
\]

\[
\left[ \frac{x_{imn}^M - x_{imn}^L}{x_{imn}^L - x_{imn}^M} \right]^{x_{imn}} \geq \lambda \quad \forall \ i, m, n
\]

\[
c_{il}^L \leq c_{il} \leq c_{il}^D \quad \forall \ i, l
\]

\[
\max \left[ x_{imn}^L, x_{imn}^{MIN} \right] \leq x_{imn} \leq x_{imn}^{MAX} \quad \forall \ i, m, n
\]

\[
0 \leq \lambda \leq 1
\]

The model is a multiobjective formulation maximizing minimum satisfaction level (\( \lambda \)). In the fuzzy constraints (2) and (3) the goals of PCA and dischargers respectively are made greater than or equal to \( \lambda \), to formulate this MAX-MIN model. The lower and upper bounds of water quality indicator \( i \) at the checkpoint \( l \) are fixed as permissible (\( c_{il}^P \)) and desirable level (\( c_{il}^D \)), respectively as set by PCA in constraint (4). The bounds of fractional removal level \( x_{imn} \) of the pollutant \( n \) from the discharger \( m \) to control the water quality indicator \( i \) in the river system, is given by constraint (5). The aspiration level and maximum fractional removal level acceptable to the discharger \( m \) with respect to \( x_{imn} \) are represented as, \( x_{imn}^L \) and \( x_{imn}^M \), respectively. The PCA
imposes minimum fractional removal levels that are also expressed as the lower bounds, $\lambda^{MIN}_{mn}$ in constraint (5). The exponents, $\alpha_m$ and $\beta_m$, appearing in constraints (2) and (3) respectively, are nonzero positive real numbers.

**Model Formulation**

To account for imprecision in the description of low water quality, Sasikumar and Mujumdar [7] and Mujumdar and Sasikumar [8] have introduced a fuzzy set based definition in place of the crisp set based definition of low water quality. The fuzzy risk of low water quality is defined as the probability of occurrence of the fuzzy event of low water quality.

Denoting the fuzzy set of low water quality, DO concentration, and fuzzy risk of low water quality by $W_l$, $c_l$, and $r_l$, respectively, the fuzzy risk can be expressed in discrete form, as

$$ r_l = \sum_{c_{min}}^{MAX} \mu_{W_l}(c_l) \rho(c_l) $$

(7)

where $c_{min}$ and $c_{max}$ are the minimum and maximum concentration levels of DO obtained from MCS at checkpoint $l$. A typical membership function of low water quality, $\mu_{W_l}(c_l)$ is expressed as,

$$ \mu_{W_l}(c_l) = \left[ (c^o_l - c_l)/(c^o_l - c^L_l) \right] $$

(8)

Details of the procedure for evaluating fuzzy risk may be found in Subbarao et. al. [5]. In that work, Sensitivity analysis and First Order Reliability Analysis are performed for screening the basic variables, and Monte-Carlo simulation is used for deriving the probability density function of the water quality indicator.

Here, a nonlinear multiobjective optimization model is developed to minimize the fuzzy risk of low water quality in river water quality management. The model consists of two objective functions, (i) to maximize the satisfaction level resulting from Fuzzy Waste Load Allocation Model (FWLAM) for base values of input variables and (ii) to minimize the sum of the risks of low water quality at all the checkpoints. The risk minimization model considers the probability density function of the output variable, as it is associated with fuzzy risk of low water quality. Mathematically the model is represented as:

Maximize $\lambda$

(9)

Minimize $\rho$

(10)

subject to
Fuzzy multiobjective programming [9] is used to solve the problem. Solving the model for each of the two objective functions at a time, the best and worst values of the objective functions are evaluated. Using the best and worst values of \( \lambda \) and \( \rho \), appropriate membership functions are developed for each of the objective functions. The membership functions are expressed as follows:

\[
\mu_{\lambda} = \left( \frac{\lambda - \lambda^{-}}{\lambda^{+} - \lambda^{-}} \right)^{\varphi} \quad (17)
\]

\[
\mu_{\rho} = \left( \frac{\rho - \rho^{-}}{\rho^{+} - \rho^{-}} \right)^{\eta} \quad (18)
\]

where, \( \mu_{\lambda} \) = membership function for \( \lambda \); \( \lambda^{+} \) = best value of \( \lambda \); \( \lambda^{-} \) = worst value of \( \lambda \); \( \mu_{\rho} \) = membership function for \( \rho \); \( \rho^{+} \) = best value of \( \rho \); \( \rho^{-} \) = worst value of \( \rho \).

The exponents, \( \varphi \) and \( \eta \), appearing in constraints (19) and (20) respectively, are non-zero positive real numbers. Assignment of numerical values to these exponents is subject to the desired shape of the membership functions and may be chosen appropriately by the decision maker. With the membership functions of the two objectives the following max-min multiobjective programming is developed.

Maximize \( \varepsilon \)

subject to

\[
\left[ \frac{\lambda - \lambda^{-}}{\lambda^{+} - \lambda^{-}} \right]^{\varphi} \geq \varepsilon \quad (20)
\]

\[
\left[ \frac{\rho - \rho^{-}}{\rho^{+} - \rho^{-}} \right]^{\eta} \geq \varepsilon \quad (21)
\]

\[
\frac{\left( c_{il} - c_{il}^{-} \right)}{\left( c_{il}^{+} - c_{il}^{-} \right)} \geq \lambda \quad \forall \ i, l \quad (22)
\]

where, \( \rho \) = sum of fuzzy risk of low water quality at all the check points and \( X = Vector \) of fractional removal levels.
In the model a new variable, goal fulfillment level ($\varepsilon$) is introduced. The objective function (19) along with the minimum membership value constraints (20 and 21) ensure the maximization of minimum goal fulfillment level.

As the model results in a nonlinear optimization problem, Probabilistic Global Search Laussane (PGSL), a global search algorithm is used to solve the problem. The algorithm is based on the assumption that better sets of points are more likely to be found in the neighborhood of good sets of points, therefore intensifying the search in the regions that contain good solutions. Details of the algorithm may be found in Raphael and Smith [10].

**MODEL APPLICATION**

Application of the models are illustrated through a case-study of Tunga-Bhadra River system shown schematically in Fig. 1. The Tunga-Bhadra River is a perennial river formed by the confluence of Tunga and Bhadra rivers, both tributaries of the Krishna River, in southern India. The river has two other tributaries, the Kumadavati and Haridra rivers. The river network is discretized into 15 reaches depending on the river morphology and river environment. The river receives the waste loads from eight major effluent points. Non-point source of pollution is also taken into account in the present study. Details of the data and the uncertainty information of the basic variables are taken from Central Water Commission (CWC), Karnataka State Water Resources Development Organisation (KSWRDO), Karnataka State Pollution Control Board (KSPCB) and Subbarao et al. [5]. A minimum fraction removal level of 35% and a maximum treatment level of 90% are assumed for the dischargers. 14 checkpoints are selected in the river reach depending on the positions of dischargers and the confluence of tributaries.

The model is solved three different values of $\phi$ and $\eta$: 0.8, 1 and 1.25. Taking all the combinations, 9 sets of analysis have been performed in the present study. For constrained optimization bracket operator penalty term is used.

Table 1 presents the fractional removal level for dischargers as determined from the risk minimization model. A total 10 sets of results are presented including the result of FWLAM. Figure 2 shows that optimal $\lambda$ value should be the same for the sets of $\phi = 0.80$, $\eta = 0.80$, $\phi =$
1.00, \( \eta = 1.00 \); and \( \varphi = 1.25, \eta = 1.25 \). The result shows that for all the three cases the optimal \( \lambda \) value is 0.230. \( \varphi = 0.80, \eta = 1.25 \) and \( \varphi = 1.25, \eta = 0.80 \) result in the two extreme solutions for the optimal values of \( \lambda \), 0.194 and 0.261 respectively.

The result shows that, applying risk minimization model, it is possible to reduce the fuzzy risk of low water quality at critical checkpoints by significant amount. For example, for the case of linear membership functions (i.e. \( \varphi = 1.00, \eta = 1.00 \)), at the first two checkpoints (locations 1-3 and 2-3) risks of low water quality have been reduced by 7.71% and 12.68%. In the last 3 reaches (location 13-12, 15-2 and 15-19), the risk is reduced by 4.48%, 5.55% and 6.83%, respectively, as compared to FWLAM.

**CONCLUSIONS**

Methodology for minimization of risk in a river water quality control problem is presented. The policy derived from the risk minimization model is compared with those of FWLAM. The resulting fractional removal levels have been increased, but it is possible to reduce the risk of low water quality significantly by applying this models. Risk minimization model does not limit its application to any particular pollutant or water quality parameter in the river system. Given appropriate models for spatial and temporal distribution of the pollutant in a water body, the methodology can be used to reduce the risk. In a general sense, it is adaptable to various environmental system where a sustainable and efficient use of environment is of interest.
International Conference on “Hydrological Perspectives for Sustainable Development” HYPESD-2005

<table>
<thead>
<tr>
<th>$\varepsilon$</th>
<th>FWLAM $\phi=0.80$ $\eta=0.80$</th>
<th>$\phi=0.80$ $\eta=1.00$</th>
<th>$\phi=0.80$ $\eta=1.25$</th>
<th>$\phi=1.00$ $\eta=0.80$</th>
<th>$\phi=1.00$ $\eta=1.00$</th>
<th>$\phi=1.00$ $\eta=1.25$</th>
<th>$\phi=1.25$ $\eta=0.80$</th>
<th>$\phi=1.25$ $\eta=1.00$</th>
<th>$\phi=1.25$ $\eta=1.25$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>0.423</td>
<td>0.615</td>
<td>0.577</td>
<td>0.535</td>
<td>0.583</td>
<td>0.544</td>
<td>0.509</td>
<td>0.560</td>
<td>0.516</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.230</td>
<td>0.213</td>
<td>0.194</td>
<td>0.247</td>
<td>0.230</td>
<td>0.215</td>
<td>0.261</td>
<td>0.244</td>
</tr>
<tr>
<td>$x_1$</td>
<td>0.667</td>
<td>0.773</td>
<td>0.783</td>
<td>0.792</td>
<td>0.764</td>
<td>0.773</td>
<td>0.782</td>
<td>0.755</td>
<td>0.764</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x_2$</td>
<td>0.665</td>
<td>0.772</td>
<td>0.781</td>
<td>0.791</td>
<td>0.759</td>
<td>0.773</td>
<td>0.781</td>
<td>0.753</td>
<td>0.759</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x_3$</td>
<td>0.624</td>
<td>0.730</td>
<td>0.746</td>
<td>0.742</td>
<td>0.737</td>
<td>0.654</td>
<td>0.746</td>
<td>0.739</td>
<td>0.737</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x_4$</td>
<td>0.555</td>
<td>0.773</td>
<td>0.782</td>
<td>0.790</td>
<td>0.763</td>
<td>0.773</td>
<td>0.782</td>
<td>0.753</td>
<td>0.763</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x_5$</td>
<td>0.437</td>
<td>0.753</td>
<td>0.742</td>
<td>0.676</td>
<td>0.669</td>
<td>0.749</td>
<td>0.742</td>
<td>0.750</td>
<td>0.669</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x_6$</td>
<td>0.567</td>
<td>0.772</td>
<td>0.781</td>
<td>0.780</td>
<td>0.756</td>
<td>0.769</td>
<td>0.781</td>
<td>0.709</td>
<td>0.756</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x_7$</td>
<td>0.448</td>
<td>0.773</td>
<td>0.782</td>
<td>0.792</td>
<td>0.763</td>
<td>0.773</td>
<td>0.782</td>
<td>0.751</td>
<td>0.763</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x_8$</td>
<td>0.603</td>
<td>0.771</td>
<td>0.782</td>
<td>0.790</td>
<td>0.762</td>
<td>0.773</td>
<td>0.782</td>
<td>0.750</td>
<td>0.762</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_1$</td>
<td>0.3786</td>
<td>0.3016</td>
<td>0.2948</td>
<td>0.2878</td>
<td>0.3080</td>
<td>0.3015</td>
<td>0.2948</td>
<td>0.3146</td>
<td>0.3080</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_2$</td>
<td>0.5950</td>
<td>0.4678</td>
<td>0.4566</td>
<td>0.4452</td>
<td>0.4791</td>
<td>0.4682</td>
<td>0.4566</td>
<td>0.4892</td>
<td>0.4791</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_3$</td>
<td>0.1995</td>
<td>0.1893</td>
<td>0.1884</td>
<td>0.1875</td>
<td>0.1903</td>
<td>0.1894</td>
<td>0.1884</td>
<td>0.1911</td>
<td>0.1903</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_4$</td>
<td>0.5716</td>
<td>0.5630</td>
<td>0.5627</td>
<td>0.5623</td>
<td>0.5634</td>
<td>0.5630</td>
<td>0.5627</td>
<td>0.5638</td>
<td>0.5634</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_5$</td>
<td>0.3516</td>
<td>0.3250</td>
<td>0.3237</td>
<td>0.3226</td>
<td>0.3263</td>
<td>0.3250</td>
<td>0.3237</td>
<td>0.3277</td>
<td>0.3263</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_6$</td>
<td>0.2677</td>
<td>0.2516</td>
<td>0.2508</td>
<td>0.2501</td>
<td>0.2524</td>
<td>0.2516</td>
<td>0.2508</td>
<td>0.2532</td>
<td>0.2524</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_7$</td>
<td>0.2711</td>
<td>0.2563</td>
<td>0.2557</td>
<td>0.2550</td>
<td>0.2571</td>
<td>0.2563</td>
<td>0.2557</td>
<td>0.2578</td>
<td>0.2571</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_8$</td>
<td>0.2978</td>
<td>0.2865</td>
<td>0.2860</td>
<td>0.2857</td>
<td>0.2872</td>
<td>0.2865</td>
<td>0.2860</td>
<td>0.2876</td>
<td>0.2872</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_9$</td>
<td>0.3084</td>
<td>0.2985</td>
<td>0.2981</td>
<td>0.2977</td>
<td>0.2991</td>
<td>0.2985</td>
<td>0.2981</td>
<td>0.2995</td>
<td>0.2991</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_{10}$</td>
<td>0.2741</td>
<td>0.2663</td>
<td>0.2659</td>
<td>0.2656</td>
<td>0.2667</td>
<td>0.2663</td>
<td>0.2659</td>
<td>0.2670</td>
<td>0.2667</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_{11}$</td>
<td>0.2847</td>
<td>0.2622</td>
<td>0.2614</td>
<td>0.2607</td>
<td>0.2632</td>
<td>0.2622</td>
<td>0.2614</td>
<td>0.2644</td>
<td>0.2632</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_{12}$</td>
<td>0.3294</td>
<td>0.2846</td>
<td>0.2832</td>
<td>0.2819</td>
<td>0.2864</td>
<td>0.2846</td>
<td>0.2832</td>
<td>0.2888</td>
<td>0.2864</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_{13}$</td>
<td>0.4433</td>
<td>0.3879</td>
<td>0.3857</td>
<td>0.3838</td>
<td>0.3904</td>
<td>0.3878</td>
<td>0.3857</td>
<td>0.3936</td>
<td>0.3904</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r_{14}$</td>
<td>0.4625</td>
<td>0.3944</td>
<td>0.3912</td>
<td>0.3887</td>
<td>0.3976</td>
<td>0.3942</td>
<td>0.3912</td>
<td>0.4018</td>
<td>0.3976</td>
</tr>
<tr>
<td>$\rho$</td>
<td>5.0353</td>
<td>4.5350</td>
<td>4.5042</td>
<td>4.4747</td>
<td>4.5672</td>
<td>4.5351</td>
<td>4.5042</td>
<td>4.6000</td>
<td>4.5672</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**NOMENCLATURE**

- \( c_{il} \) = Concentration of water quality indicator, \( i \) at checkpoint, \( l \);
- \( c_{il}^L, c_{il}^D \) = Desirable and permissible levels for \( c_{il} \);
- \( r_l \) = Risk at checkpoint, \( l \);
- \( x_{imn} \) = Fraction removal of the pollutant, \( n \) from discharger, \( m \) to control the water quality indicator, \( i \);
- \( x_{imn}^L, x_{imn}^M \) = Aspiration and maximum acceptable fraction removal levels;
- \( \varepsilon \) = Overall satisfaction level of risk minimization model;
- \( \lambda \) = Satisfaction level of FWLAM;
- \( \rho \) = Sum of the risks at all the checkpoints;

**Subscript**

- \( i \) = water quality indicator;
- \( l \) = checkpoint;

---

Fig. 2 Membership Functions of Objective Functions

![Membership Functions of Objective Functions](image-url)
m = discharger;  
n = pollutant;  

REFERENCES  