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"Modelling for Seawater Quality Management"

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Invited paper

Modelling for Seawater Quality Management

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To find an optimum pollution management plan for coastal sea or a lake, first existing measurements of currents and concentrations are used in order to reconstruct movement of water and transport of pollutants. Then models are used to predict effect of various management plans. Finally an optimum management plan is selected. Three case studies are reviewed to illustrate the procedure.

Keywords: optimum environmental management, seawater, lake, phosphorus, total suspended matter, heavy metals, toxic substances, current field, concentration field, Izmit Bay, Punat Bay.

1. Introduction

There is a rising concern about the quality of water in the sense of pollution. Atmospheric water becomes polluted on its way from the place of evaporation to the place of deposition where it may fall as a polluted rain (acid rain is a familiar example). Freshwater is being polluted on the way from its spring until it reaches the sea. Ground water gets polluted by passing from the surface through the soil. Finally, seawater is being polluted by direct disposal of waste waters into the sea and by polluted rivers.

Although in this paper I will deal with seawater only, methods for solving freshwater pollution problems do not differ significantly.

Since majority of permanent pollution sources are located on the coast, seawater becomes polluted first in the coastal zone, especially in bays and estuaries. Unfortunately, the zone is used increasingly for recreational activity, fishing and fish farming. Hence, there is a conflict of interests: some want to dump their waste into the sea while others need clean sea for food and recreation. It is the resolution of this conflict, and not the ecology of the sea, that has been the primary drive so far of existing research, technological implementation and lawmakers' activity.

Following research recommendations, lawmakers around the world have implemented a definition of water quality consisting of four categories. The seawater suitable for all human activities is termed the first category. In the second category is the seawater suitable for all human activities except fish farming. In the third category is the seawater which is not suitable for human recreation, but may be used for fishing. Seawater of the fourth category is not suitable for any human activity.

The definition of seawater quality is based on values of 10 to 15 parameters (depending on the country) such as total coliform bacteria, pH, temperature change, visible waste, dissolved oxygen, total suspended matter, oil and its derivatives, surface active substances, radioactivity and toxic substances.

Why is there a need to simulate seawater quality? When a water body is found to be polluted, would it not be simpler just to shut off all pollution sources? Indeed, this is done wherever economically profitable. In majority of cases however, the cost would be enormous (Constanca et al., 1997). The very existence of pollution sources is linked to economy. Often it is much cheaper to transport pollutants to a place where they would not harm people than to clean or turn them into useful products. Although the pressure to clean up coastal waters is mounting and simulation of seawater quality is being used as one of the tools in the process, while more efficient production and cleanup technologies are being developed, polluted coastal waters are still increasing in area.

2. The Role of Seawater Quality Simulation

2.1. Direct simulation of pollutant dispersion

Suppose that an area has been found to have unacceptable water quality. Let location and intensity of all the sources be known. How much is each source contributing to the observed pollution of seawater in the given area or at a given location? This is often one of the first questions that managers ask. The answer to this question is important, because it enables managers to set finances aside and tackle pollution problem according to a fair scheme. Clearly, the fair scheme may deviate significantly from the rule "financial contribution is proportional to pollution influx at the source" because it may be that pollution from the major source does not enter, or may enter only slightly, the area of interest.

I see two possible ways to answer the question. The first is experimental: release from sources of pollution as many different tracers as there are sources and monitor their concentration in the area of interest. This is indeed done in small rivers and to a limited extent. In seawater, the proposal would run into practical difficulties due to large dilutions and hence very large cost. The alternative is to use simulation of seawater movement and corresponding transport of pollutants.

2.2. Estimation of sources

Let us now weaken the above hypothesis on sources and suppose that not all major sources (i.e. locations and/or intensities) of pollution are known in the area of interest. This regularly turns out to be the case. Clearly the estimation of sources is important for any subsequent simulation. When sources are diffuse, the intensity and even location may be very difficult to estimate directly. However, if the area of interest is monitored regularly, it is possible to estimate sources indirectly from pollution measurements in the sea.

Indirect estimation of sources is also often performed when verification of compliance to agreements is needed. Suppose an authority has given a license to a factory for polluting the sea up to a specified intensity. If the seawater quality is monitored, it is possible to estimate the intensity of the source and check quantitatively to what extent is the polluter acting in agreement with the license.

2.3. Simulation of management scenarios

Simulation of various seawater quality management scenarios involve answers to the following questions. To what extent should sources be reduced so that the area of interest attains desired seawater quality? How far and in which direction should a source be relocated so that its impact on the location of interest is reduced by an amount specified in advance?

Instead of reducing and relocating the sources, sometimes it is worthwhile to consider relocating the activity that requires high seawater quality. Then the questions are: a) Where is the nearest suitable location for such an activity? and b) What needs to be done to insure that seawater quality at the new location is not degraded during the life-time of the planned activity?

Presently simulation of seawater quality is the only means by which answers to the above questions can possibly be given.

2.4. Identification of pollutant extinction

Once in seawater, pollutant disperses according to the movement of seawater masses, but in addition, it may be inactivated by biological organisms or photochemical reactions, or it may attach to particles and sink. Any of these and many other processes that exist in seawater cause extinction which is manifested by a decrease in pollutant concentration. From the multitude of natural processes and a number of different pollutants, it is immediately clear that, even for the major pollutants, researchers have a huge problem in quantifying extinction processes. It is therefore not surprising that such

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knowledge is far from adequate when one attempts to simulate transport of substances in a particular coastal sea. This means that it is practically impossible to accurately simulate transport of pollutants in coastal sea by direct means.

However, by combining monitoring and simulation it is possible to estimate the totality of extinction processes and hence decrease uncertainty in predictions of seawater quality.

3. Toward a Seawater Quality Management Procedure

The restricted meaning of management in this paper is related to three steps.

3.1. Getting to know the quality of water.

This step is executed by carrying out monitoring program in the location of interest. The program consists of choosing a representative set of stations, sampling water with sufficient frequency and analyzing it by agreed measurement methods for the most likely pollutants.

In case water quality has been violated, one proceeds to estimate the meaning of the pollution problem: its extent and likely consequences. If the pollution problem poses a health risk or is likely to cause a conflict of interests, a call for solving the problem is issued.

3.2. Basis for solving the problem

3.2.1. Determining intensity of point sources

Location of major point sources is usually well known. The intensity is best determined by direct sampling at the source and at representative times. Here one must bear in mind that residential sources of some pollutants may vary three orders of magnitude within one day. Since industrial sources may vary even more, it is clear that a great care is needed to design a representative sampling program.

In practice so far, as a consequence of: a) a limited knowledge of what constitutes a representative sampling program, and b) a very limited budget, a few representative sampling programs have been performed. Therefore, sources are assessed using standards of consumption *per capita* or, in case of industrial activity, for a unit product.

3.2.2. Discovering and determining intensity of unknown (diffuse) sources

This step may be made satisfactory only if a carefully designed monitoring program is performed in conjunction with an inverse simulation procedure (Legović, Limić and Valković, 1990).

3.2.3. Determining relevant properties of the pollution carrier

The step consists of discovering movement of water, its temperature and salinity.. Temperature and salinity are indicators of seawater layers with consistent movement properties. Movement of seawater is determined by current meters (Eulerian measurements) or drifters (Lagrangian measurements).

3.2.4. Determining pollutant extinction processes

We expect that every pollutant or nutrient is to a lesser or greater degree unconservative. This means that once in water, it is degraded to other forms, taken up by biota, sedimented or resuspended.

Pollutant extinction processes are determined in the laboratory under controlled conditions. However, such experiments have been done for very few pollutants so far (Jorgensen, 1976). For example, it is known that half-life of coliform bacteria in laboratory seawater is about 40 min (GI, 1985). Alternatively, it is possible to estimate half-life of the pollutant if its concentration has been monitored in seawater.

3.2.5. Predicting the consequences of changing the intensity and/or relocating pollution sources and selection of optimum management plan.

Predictions are made of effects that possible management actions would have on the water

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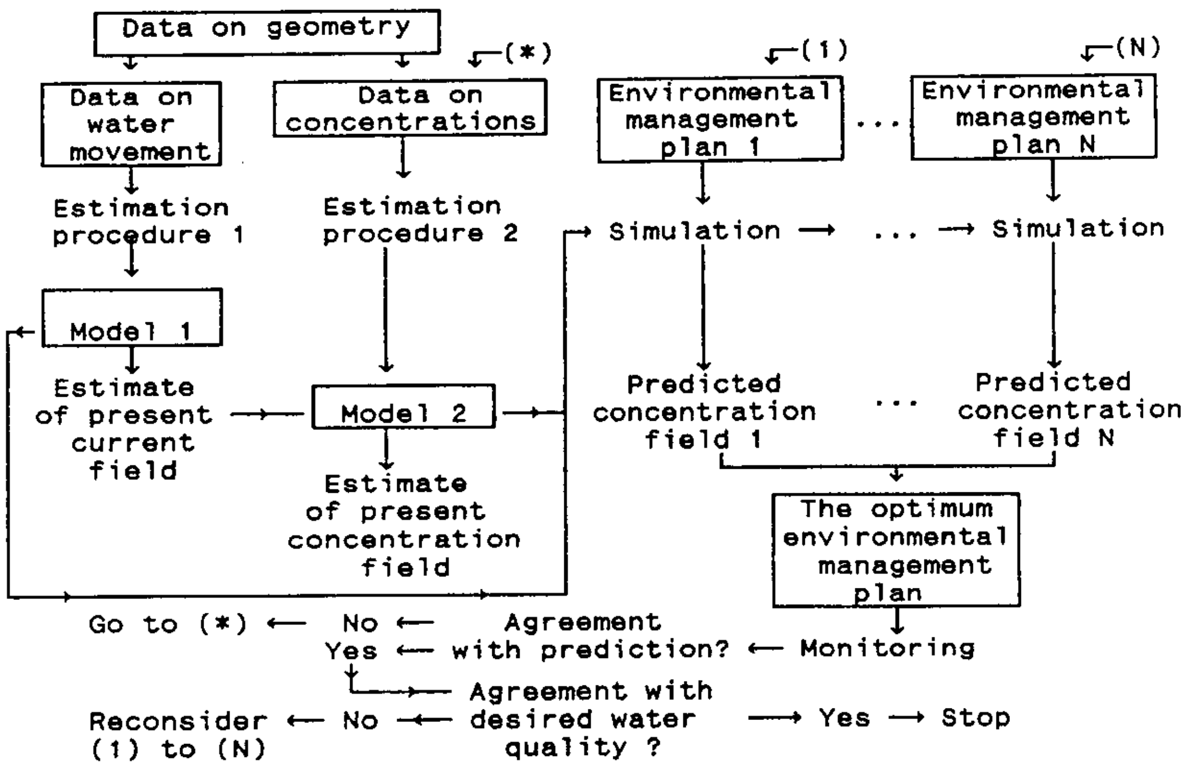

Fig. 1. Steps in constructing an optimum management plan for attaining desired seawater quality.

quality. The aim is to find the best management action and provide relevant data for the cost/benefit analysis.

The predicted concentration field may easily be connected to Maximum Allowable Concentrations in Water (MACW) that lawmakers have established for each water quality category. These limits have been set according to the existing scientific results which quantify effects of pollutants on marine life and on humans. In this paper we shall take such results as given, although it is clear that with the discovery of new effects, MACW will change in future.

Since a pollutant or a nutrient is moved around by the current field, we have to estimate this field first. Once the current field is estimated, it is used to estimate the concentration field based on the existing data on concentrations. Estimation of the concentration field must be based on relevant physical, chemical and biological principles, so that at the time one has estimated the concentration field, a justifiable model which best represents existing data is obtained.

From this point on, one uses the obtained model as a predictive tool in order to select among possible environmental plans (Figure 1).

3.2.6. Predicting monitoring needs.

Adopting a management action will require construction of adequate monitoring program to be carried out at least during the first year of operation. This is needed in order to determine whether the adopted management action is producing expected results.

3.3. Implementation

3.3.1. Engineering implementation

Implementation of a management procedure involves one or a combination of: relocation, merging, dispersing and decreasing intensity of sources and relocation of activities that require higher water quality.

3.3.2. Monitoring

Monitoring must be a part of the tentative solution and it must be able to determine whether and to what extent the implemented solution is yielding expected results. If it is, then the desired solution has been found. If not, the degree to which reengineering is needed will become obvious from a second series of simulation results. These simulations require monitoring results.

4. Transport of Substances in a Coastal Sea

For simulating transport of substances from their sources into the coastal sea. two approaches have been developed: near field and far field.

The near field extends from residential and industrial sources of pollution to at the most 5 km into the sea. In this region the source related details such as its geometry, ejection velocity and specific density of polluted water are important.

In the far field, which extends to tens of kilometers from the sources, the source related details usually are not taken into account. More important are movement of water masses. geometry of the coastal sea and extinction of the pollutant.

4.1. Near field

There are several models which take into account details related to the source and surrounding water. In this paper I shall describe only the most often used approach. It has been developed by Brooks (1960, 1973) and applied first to determine the length of the submarine outfall near Los Angeles, USA.

The approach is divided into three steps: initial dilution, secondary dilution and extinction.

Assume the coast is far from the source, seawater column has a constant depth and is not stratified.

Initial dillution, S , for point and line source is:

Point source $S_1 = 0.089 g'^{1/3} Q^{-2/3} d^{5/3}$ (1)

Line source $S_1 = 0.38 g'^{1/3} Q_m^{-2/3} d$ (2)

where $g' = g(\gamma_m - \gamma)/\gamma$, $g = 9.81 \mathrm{m/s^2}$, γ_m — weight of 1 m^3 of seawater, γ — weight of 1 m^3 of waste water, Q — influx (m^3/s), Q_m -- influx per meter length (m^2/s), d - depth of seawater column (assuming that the source is on the bottom).

For example, if $S_1 = 100$ this means that the pollutant with the concentration at the outfall C_0 will reach the surface with concentration 0.01 C_0.

In case seawater column is stratified, another pair of formulas has been developed (Fisher, 1979).

When the initial cloud is formed, it is subject to dispersion. Dispersion of the cloud is called secondary dilution:

$S_2 = \{\mathrm{erf}[[1.5/((1+8\alpha t/B^2)^3 - 1]^{0.5}]\}^{-1}$ (3)

where erf is the error function, α is the initial value of horizontal turbulent (or eddy) diffusion coefficient, t is the time since initial dilution. If v is velocity of seawater, dilution at point x along the velocity vector is obtained by substitution $t = x/v$.

Finally, the extinction is computed from:

$S_3 = C_0/C(t) = \exp(k\,t)$ (4)

where k is the extinction constant, i.e. $k = (\ln 2)/E$ where E is half-life of the pollutant in the seawater.

Total dilution is computed as a product:

$S = C_0/C(t) = S_1 S_2 S_3.$ (5)

The dilution is expected to hold along the center line of pollutant movement.

The above approach is often used to compute an approximate length ($x = L$) of the planned outfall given the concentration at the outfall C_0 and selected final concentration C_f.

A more accurate estimate of the length is obtained by taking into account stratification of the seawater column, more details related to the source and bottom topography toward the coast (Fisher, 1979).

4.2. Far field

The concentration field in a wider region around one or several sources will depend on geometry of the coastal sea, movement of seawater, location and intensity of sources and on the extinction of the pollutant.

It is clear that in order to obtain two or three dimensional picture of the concentration field one must solve the transport equation:

$$\partial C/\partial t = \alpha \Delta C - \vec{v}\nabla C - kC + Q \tag{6}$$

subject to appropriate boundary conditions.

The equation (6) is far from being written in the most general form. In fact, it is often restricted to a homogeneous layer of water and then it is applied to describe horizontal transport in a current field $\vec{v}$ with an eddy diffusion coefficient α of a pollutant whose extinction can be approximated by a first order process. However, there are serious problems in attempting to apply even the equation (6). The problems are associated with accurate estimates of α, $\vec{v}$, k, Q and the open boundary through which the coastal sea meets open sea. These estimates will depend on existing data.

4.2.1. Existing data

Geometry consisting of coastline and topography of almost any area of interest readily exist. Concerning the movement of water, data from several measurements of currents may be available. When only momentary current measurements are taken, they are of a very limited use. Several days of current measurements at intervals from 5 to 15 min are more useful because they allow one to filter out tidal currents. Measurements carried out for one or more months are indeed rare but very useful to detect residual currents. In general, current measurements of such length are too expensive and hence rare.

Sometimes there exist data on drift experiments, but they often supply evidence of surface currents only. These currents are known to be much different from the currents deeper in the water column.

Measurements of concentrations in the seawater are usually carried out on a larger number of stations and with higher frequency. Such measurements cost less and methods are available to routinely measure concentrations of many substances, especially common forms of pollutants and nutrients.

I expect the data on locations and intensity of the sources of pollution to be incomplete. At the best, direct measurements and estimates of major point sources may enable one to represent these sources within a factor of two.

Direct data on diffuse sources are an entirely different story. If direct data on approximate distributions of these sources exist, one should not expect more. Indeed, it is practically impossible to estimate intensity of these sources directly.

4.2.2. Estimating the current field

By a current field it is ment either the measured current field or the residual current field that persists for days or months. The residual field is obtained from the measured field when shorter frequencies, including tidal contribution, are filtered out. We have shown that even in areas as small as 2 km with the tidal range of 50 cm, the exchange of water attributed to tidal currents is negligible (Legović and Limić, 1989). Therefore when considering transport of substances in coastal sea, one should concentrate on the residual current field.

The residual current field may be estimated from the data according to several methods:

1) Assume that some measurements of currents have been made. The horizontal residual current field $v = (v_1, v_2)$ is sought subject to the following properties (Limić, 1984):

$$\operatorname{div} \vec{v} = 0,\ \operatorname{rot} \vec{v} = \operatorname{rot} \vec{v}_m \quad \text{and} \quad \|\vec{v} - \vec{v}_m\| \to \inf. \tag{7}$$

where $\vec{v}_m$ is the measured field.

Hence it is a solution to an optimum control problem.

2) The linearized Navier-Stokes equations with a diagonal viscosity tensor, constant pressure and forces that are proportional to velocity, may be fitted to data in the least-square-error sense (Coffou and Limić, 1985). The result is a unique residual current field that satisfies appropriate boundary conditions.

3) First, relative velocities are constructed from hydrographic data (temperature and salinity)

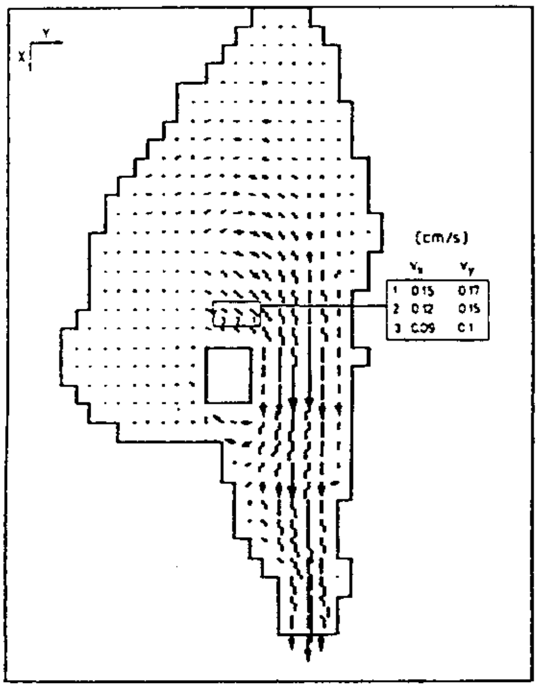

Fig. 2.

Current field with source of water inside the bay. The vertical is stretched 1.2 times (from Legović and Limić, 1989).

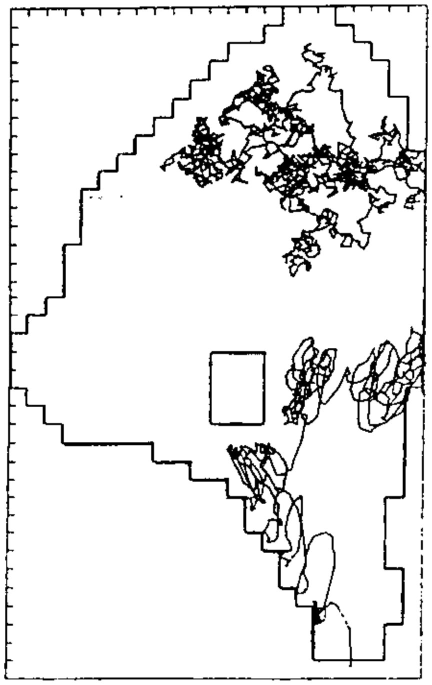

Fig. 3.

Two Monte-Carlo simulations using two estimates of the actual current field (from Limić, 1987).

using an objective analysis. Then, an objective analysis is also applied to measurements of currents. Finally the two are combined to produce the estimated current field (Limić and Orlić, 1987). The estimated field is the absolute geostrophic current field which satisfies the appropriate boundary conditions.

4) In case the area contains submarine springs and the current field is supposedly affected by the inflow of freshwater, the residual current field may still be estimated according to the method 1 or 2 above, however the condition $\operatorname{div} \vec{v} = 0$ must be substituted by $\operatorname{div} \vec{v} = m(r)$, where $m(r)$ denotes existing springs. In addition, any change in the open boundary conditions must also be formulated (Legović and Limić, 1989). The resulting optimum control problem leads to the unique residual current field. Figure 2 contains one example.

Sometimes not only residual but an estimate to the actual current field is needed, especially if high tides are present. In those cases the total current field may be represented by the sum of tidal and residual parts, where the residual part has been estimated by one of the above methods. In addition, taking into account statistical properties of current measurements, the total estimated field may be very useful for Monte-Carlo simulations of transport of particles released into the region (Figure 3). Being able to create many trajectories gives rise to the statistics as to where the particles will reside most likely at any instant after their release. In this way one can investigate pollution paths, locations where the pollutant accumulates and find locations that the pollutant is unlikely to reach. Such locations could be selected for activities that require higher water quality.

An alternative to the above approach is to run a dynamic model of water movement with the wind forcing to a steady state and then use statistics of current measurement to define Monte-Carlo simulations. Model formulation, a set of nice Monte-Carlo simulations and a comparison with satellite observations in northern Adriatic Sea may be found in Kuzmić 1991, 1993.

(7)

4.2.3. Estimating the concentration field

In order to reconstruct (estimate) the present concentration field, a transport model needs to be solved in a two dimensional domain. If we consider that the velocity field has been obtained by one of the above procedures and that the eddy diffusion coefficient has been estimated using the formula: $AL^{4/3}$ where L is characteristic scale of the region and A is constant (Okubo, 1980), it remains to determine the extinction function. This can be done if measurements of pollutant concentrations are available. In order to deal with equation (6) such data must be taken over an interval of time. This is indeed very rarely the case. More often data on concentration are taken over the region once in a season. Residual currents too are assumed to hold stationary over the season. Hence one seeks the solution to stationary or average transport model which is fitted to the existing data in such a way that the least-square-error criterion is met i.e.

$$-\alpha\Delta C + \vec{v}\nabla C + kC = Q, \qquad (8)$$

and

$$\sum_{i=1}^{n}(C_i - C_{m_i})^2 \rightarrow inf. \qquad (9)$$

where C is computed and C_m is measured concentration. The admissible boundary conditions include measurements of concentration at the sources, measured or estimated concentration at open boundaries and the Neumann condition on the rest of the coastal boundary.

In case the region of interest is a part of a larger coastal sea, the eddy diffusion coefficient will not be well approximated by the power law. Then it can also be estimated by the same inverse procedure as above (Legović et al., 1989).

Often, some sources are unknown and they may be point or diffuse. Such sources may be estimated using a control problem that is an extension to the one above (Legović and Limić, 1991).

An additional problem arises when data on concentrations in the water column are not very reliable. If the data on measurements of concentrations in the sediment exist and the region of interest is not more than 50 m deep, the concentration field in the water column may be better estimated from the data in the sediment through a scaling procedure (Legović et al., 1990a).

4.2.4. Predictions

By now it has become obvious that we are interested in fitting current and concentration fields to the existing data by using the mechanisms that produce these fields. Otherwise such fits would have no predictive value.

Once models are selected and parameters estimated, based on the existing data, they are ready to be used as predictive tools to calculate concentration fields that will result from implementation of an environmental management plan (EMP) which proposes to change the distribution of existing sources. Reliability of prediction is based on both existing data and validity of hypotheses upon which the models have been built.

Building experience in processing various data sets and experimenting with realistic hypotheses, enables one to predict the effect of an EMP with a smaller error margin. The consequence is that less reengineering will be needed once a tentative optimum EMP is implemented.

4.3. The software package: RECON

The ideas behind the development of a tool to assist in the management of coastal sea is to automatically construct models satisfying as many physical, chemical and biological laws as the existing data permit. The computer should do and remember all that is needed to arrive at a desired solution. The user should only concentrate on the problem: decide what need to be done, enter the existing data, and compare predictions in order to select the optimum plan.

The software package RECON is one such example (Legović and Limić, 1992). It includes more than 40 modules which work interactively to produce reconstructed current and concentration field first. In the second instance it uses identified models to produce predicted concentration field.

The modules perform the following functions.

1. Recognition of numerous types of data that might exist i.e. data on geometry, currents and concentrations.

(8)

2. Checking mutual consistency of data.
3. Automatic selection of methods based on existing data.
4. Interactive building of models and boundary conditions.
5. Estimating parameters for the models (solving inverse problems).
6. Reconstructing (estimating) the existing current field.
7. Ability to experiment with the existing current and concentration data. This feature has been very useful in redesigning monitoring programs.
8. Reconstructing (estimating) the existing concentration field.
9. Calculation of a complete mass balance of any conservative or unconservative substance in the coastal sea or a lake.
10. Prediction of concentration fields following various EMPs.

The package has been used for finding the optimum EMPs, performing environmental impact assessment studies, teaching future environmental engineers in ecology, environmental engineering, geography, geology and marine sciences; finding mass balance of substances in coastal seas and lakes and for discovery of sources of various substances. In the following section three studies are presented using RECON package.

5. Case Studies

5.1. "B. Montanari" accident

The ship loaded with 1332 t of vinyl chloride in four nonremovable containers sank into the open sea of the Kornati islands (Figure 4) which are situated in the middle of the east side of the Adriatic Sea. The fluid was carcinogenic and flammable. Following the accident, several problems had to be addressed: Is the ship leaking the substance into the sea? If it is, what is the intensity and how much of the material has leaked so far? What area need to be closed for: a) trespassing; b) fishing? What is the area of restricted actions (due to possible explosion and intoxication) during each phase of the rescue operation? In case of the major leak during the rescue operation, what area will reach values that exceed MACW? For how long should such an area be closed?

During a controlled leak, from measurements of concentrations of vinyl chloride around the wreck, estimates of the following parameters in the non-stationary transport equation (6) were obtained: the angle into which the substance is leaking (γ), horizontal eddy diffusion coefficient (α), the extinction rate (k) and the source Q These parameters were obtained by solving the inverse problem for the transport equation. Most parameters were obtained as a function of velocity. Then, using the value of v obtained from measurements of currents, values of unknown parameters were calculated. The influx rate of the substance was found to agree with an entirely different indirect method.

Estimation of α and k and the knowledge of v near the ship made it possible to calculate the area of restricted access as a solution to the direct boundary value problem for the transport equation. The result was needed in order to avoid accidents due to possible explosion or intoxication of the personnel involved in the the rescue operation.

Based on measurements of currents, the current field in the larger region was estimated. Using the estimated current field and parameters estimated from concentration measurements adjacent to the ship, predictions of the concentration field in the larger region were made. Predictions covered for several possible intensities of unintentional spills.

Since measurements of currents were made during December while the rescue operation was to take place during the following May, it was necessary to predict concentration field following the change in the current field. A number of scenarios were calculated in order to guide the rescue operation (for one example see Figure 5). The operation involved underwater transport of the wreck into the bay of Remetić and unloading into another suitably equipped ship. The predictions allowed the appropriate region to be closed for fishing and establishment of measurement stations during and after the rescue operation. Computations of the areas to

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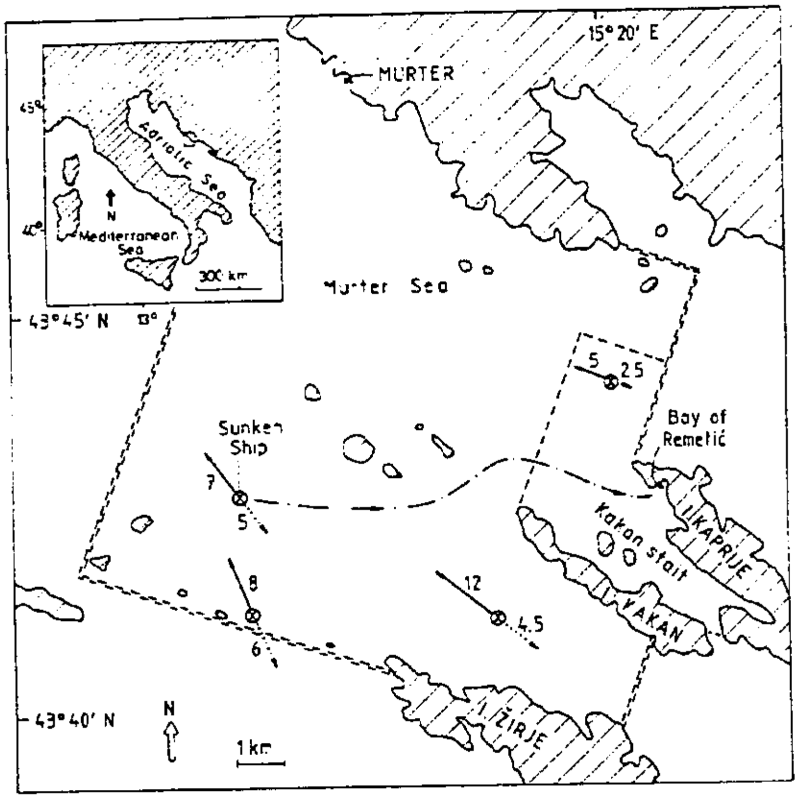

Fig. 4.

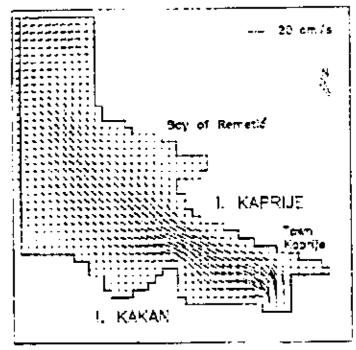

Fig. 5a.

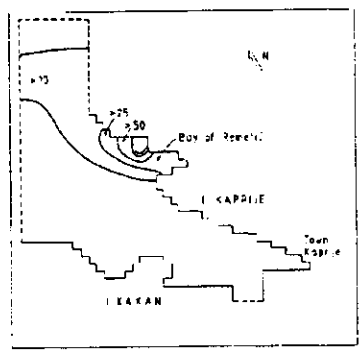

Fig. 5b.

Fig. 4. Position where the ship had sank and location where it was later transported.
Fig. 5 a) The residual current field and
b) the concentration field around the location of unloading (from Legović and Limić, 1990).

be evacuated in case of a major spill were also performed.

Computations involved solutions to the mixed problem for the transport equation. In addition, Monte-Carlo simulations were performed on a number of stochastic realizations of the current field. The realizations were constructed from the statistics of the current measurements in December. The details may be found in Legović and Limić, 1990.

5.2. Punat Bay

Punat bay is situated on the south side of the island of Krk which itself is located on the northeast side of the Adriatic Sea. The problem in the Punat Bay may be summarized as follows. In the process of expanding the present marina, a concern was expressed as to whether the present quality of water in the bay is satisfactory and, if not, how much should each responsible party contribute to the cleanup of the bay (Figure 6).

Performed concentration measurements gave a sketchy picture of the water quality. In addition, the sources in the bay were largely unknown.

The task was to discover the sources of various pollutants, mainly heavy metals. The justification of obtained sources had to come from the agreement between obtained concentration field and measurements.

For this purpose, first the current field had to be estimated. The difficulty was that sources of freshwater became evident from measurements of the salinity and hence the current field had to reflect the influence of freshwater sources. The procedure mentioned in section 4 was constructed. The resulting field is shown in Figure 2.

Based on the current field, we were ready to consider the average transport equation for a

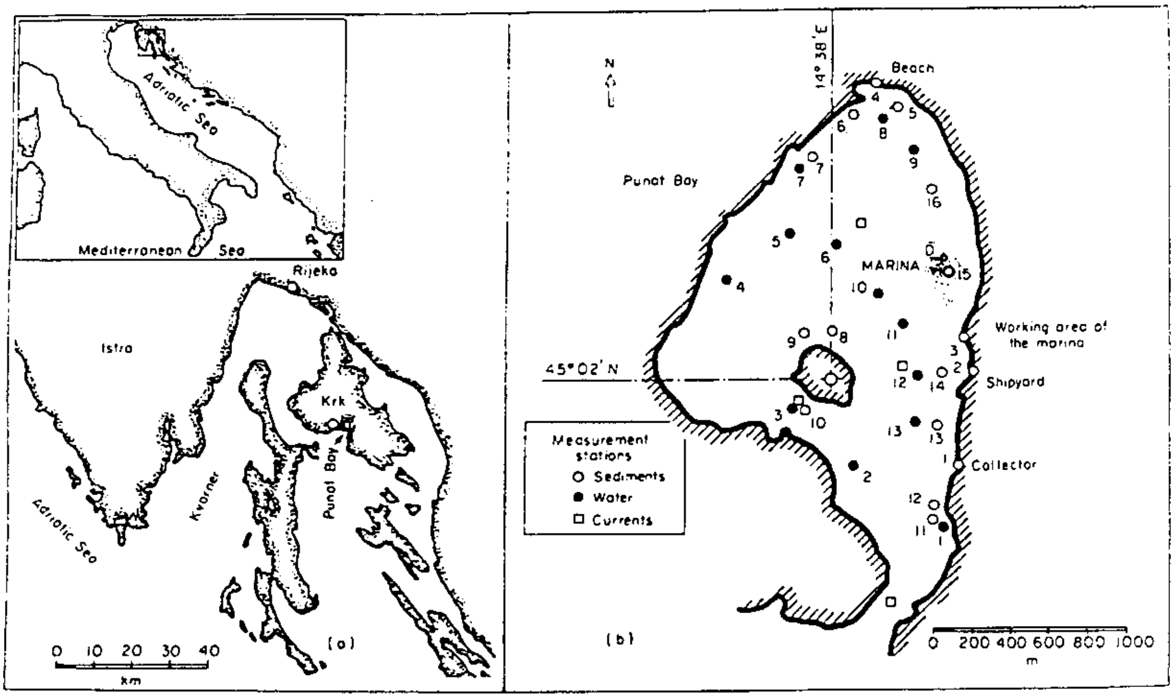

Fig. 6. Shape of the Punat Bay.

pollutant in the bay. The averaging was performed over a time interval spanning several tidal periods.

For some heavy metals, the data on concentration in water were less reliable than concentrations in the sediment, hence the latter was used to construct the concentration field. Such a concentration field had to be scaled to at least one reliable concentration measured in water. If one does not know which measurement in water is the most reliable, then the criterion stating that the computed mean is equal to the measured mean in the water may be used. The resulting concentration field for Pb in water is given in Figure 7.

The constraint that is used to estimate unknown parameters (the extinction rate and the distribution of the sources) is the least- square-error between measured and computed results. In addition, the solution is subject to the appropriate boundary conditions for the equation (8). If N sources need to be discovered then one inverse and N direct problems need to be solved.

In case of the Punat Bay five sources of three pollutants (Zn, Cu and Pb) were estimated. Results are summarized in the Table 1.

When all the parameters became known, it was easy to solve the corresponding transport equation with any combination of inputs. (The concentration field if only marina were present is given in Figure 8.) This means that any environmental management plan could have been assessed and the optimum one selected.

%	marina	collector	shipyard	marina working area	beach*
Zn	20.2	35.2	9.6	15.8	19.2
Cu	15.4	25.8	19.1	25.4	14.3
Pb	17.1	26.8	16.6	24.1	15.4

Table 1. Percentages of the contribution to the total inflow of Zn, Cu and Pb by the five sources. * beach — means that a diffuse source has been discovered on the location of the beach. Later on it was found out that the source originates from an uphill community which does not have a sewage system so the waste waters came to the vicinity of the beach through the soil.

(11)

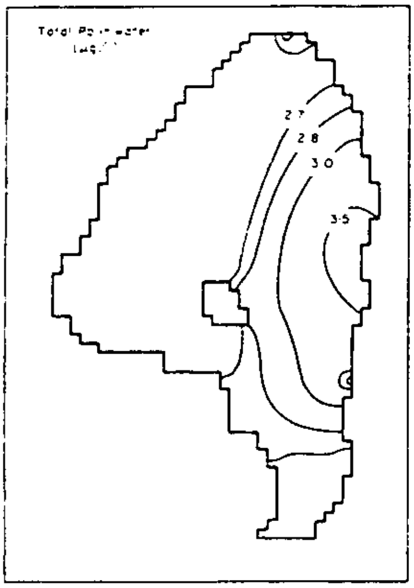

Fig. 7.
Estimated concentration field including all sources.

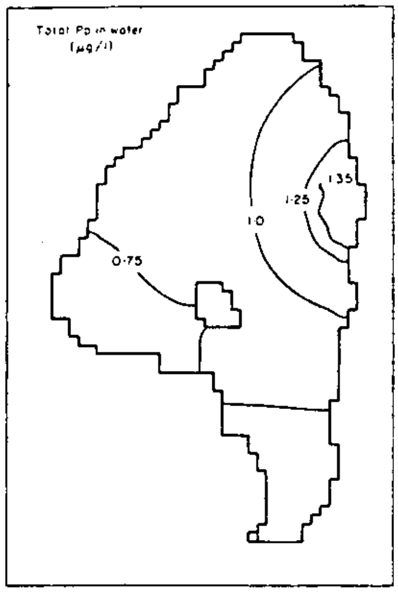

Fig. 8.
Estimated concentration field due to marina only (from Legović, Limić and Valković, 1990).

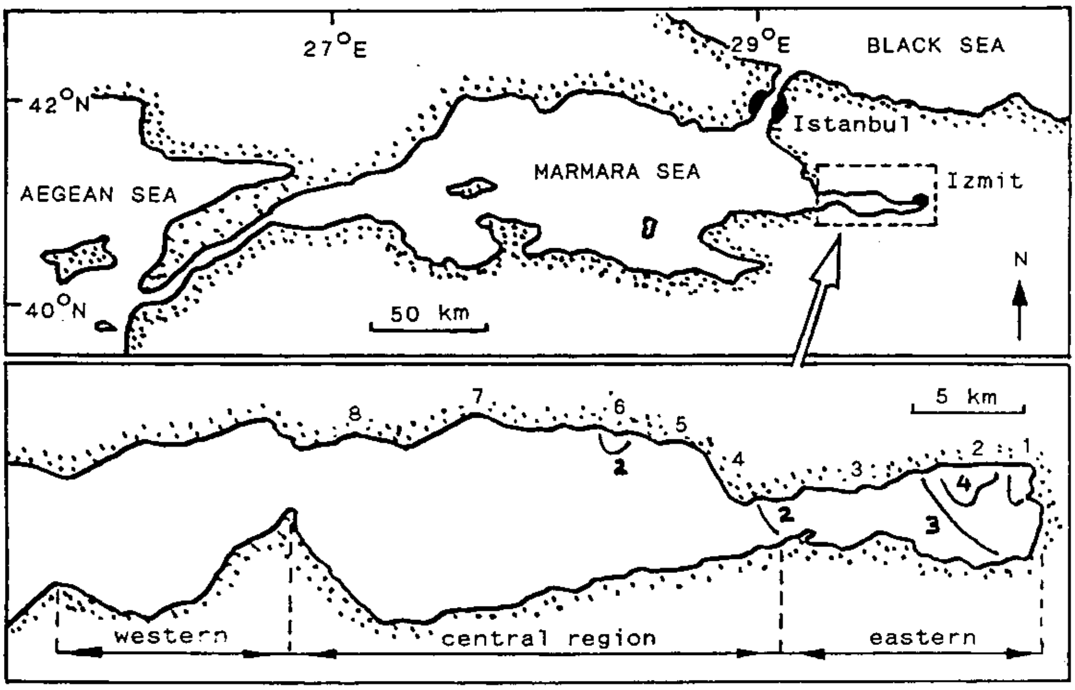

Fig. 9. Distribution of toxicity in the Izmit Bay. Isolines 2, 3 and 4 refer to four simulated cases. (according to Legović, 1997)

It is worthwhile to note that the underlying optimum control problem involved in estimating point and diffuse sources have the unique solution. The solution is unique under certain conditions related to the extinction rate, distribution of inputs and the distribution of measuring points.

This shows that monitoring results are closely related to the ability to determine sources. In another words, if inappropriate monitoring had been done, it would have been impossible to uniquely determine the sources. Even worse, inappropriate monitoring may lead to spurious and misleading results. From this evidence only (although there are many other reasons too) we may conclude that monitoring without careful modelling is mainly a waste of money and effort.

5.3. Izmit Bay

Izmit Bay is located next to the Bosphorus on the Anatolian side of the Marmara Sea (Figure 9). Along its northern coast and owing to the vicinity of Istanbul, about 85% of Turkish industry is located together with significant residential areas. Although a significant efforts have been made to process all industrial sources, a concern was expressed about seawater quality in the bay due to the desire of residential communities to use seawater for recreational purposes. A study similar to the one presented above for the Punat Bay showed that the existing distribution of total suspended matter, which is the major water quality parameter in the bay, can not be accounted for by considering its sources neither along the coast of the bay, nor through the exchange with the Marmara Sea (Legović et al., 1997). Instead, the existence of suspended matter has been linked to phosphorus sources. Once in seawater, phosphorus is consumed by a phytoplankton which in turn makes the majority of observed suspended matter. This means that instead of direct sources of suspended matter along the coast, one has to concentrate on sources of phosphorus. Furthermore, it was found that, unlike in the rest of the Mediterranean, occasionally not phosphorus but natural concentration of silica is limiting phytoplankton growth (Morkoç et al., 1997). Curiously, a similar phenomenon has been found in the northern Adriatic (Justić et al., 1995). The finding indicates that phosphorus sources must be reduced significantly before an improvement in water quality is expected.

In this case study let us concentrate on an unusual application of the transport equation (8): simulation of impact of unknown toxic substances in coastal sea.

In a series of experiments it was shown that some unknown substances inhibit uptake of nutrients present in wastewaters (Okay et al., 1996). The inhibition was decreasing with the decrease of the wastewater present in seawater. The experiments were made with wastewater from each major source. Suppose that there is a critical dilution d (indeed regularly found in experiments) at which the inhibition of uptake is zero. Let us denote with $d * Q_i$ the inflow of unknown toxic substance(s) from the source i. If we take the residual current field reconstructed for each season and somehow set the extinction coefficient (k) of toxic substances, we would be able to simulate the effect of unknown toxic substances (but not the concentration). It has been found that the coefficient k for various substances such as phosphorus (Legović et al., 1989; Legović et al., 1995), vinyl chloride (Legović and Limić, 1990), total suspended solids (Legović et al., 1997) heavy metals (Legović et al., 1990a; Legović et al. 1990b) may vary between 1 and 23 days. Assuming that to some extent phytoplankton avoids toxic substances, let $k = 24$ days.

Results of simulations for four characteristic situations occurring in Izmit Bay are presented in the Table 2.

Let us mention two curious conclusions that follow from these simulations:

1) Toxic substances present in wastewaters are likely to inhibit phytoplankton uptake well into the region of coastal sea where nutrient concentrations are higher. This means that if a solution of an ecological model:

$$\frac{\partial C}{\partial t}=\alpha\Delta C-\vec{v}\nabla C_i+f_i(C_1\ldots C_n)+Q_i,\ i=1,\ldots,n \tag{10}$$

where there are m ($m < n$) nutrients and $n - m$ phytoplankton, zooplankton and fish species, with appropriate boundary conditions, corresponds exactly to measured concentrations i.e.

$$\sum_{j=1}^{k}\sum_{i=1}^{n}(C_{i,j} - Cm_{i,j})^2 = 0. \tag{11}$$

during all of k measurements in the region, then the model must have been miscalibrated

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Conditions over the bay	Region of the bay where uptake is inhibited
summer, $v = 0$, negligible phytoplankton concentration, $k = 365$ days	throughout the bay
winter, v up to 20 cm/s, negligible phytoplankton concentration, $k = 365$ days	throughout the east part of the bay
summer, $v = 0$, phytoplankton concentration is high, $k = 24$ days	north half of the the east part
winter, v up to 20 cm/s phytoplankton concentration is high, $k = 24$ days	2 to 3 km from major sources in the east part

Table 2. Distribution of toxicity in the bay.

(Legović, 1997). Since toxicity could not have been built in any model so far, a well calibrated ecological model had to exceed (not correspond to) phytoplankton concentration found in the coastal region.

2) In the process of nutrient uptake, phytoplankton probably takes up toxic substances as well and deactivates them to some extent. As a consequence, coastal waters operate as giant, although rather inefficient, wastewater treatment plants.

We have examined above the inhibition of nutrient uptake in phytoplankton, but how far from sources are coastal waters toxic to fish remains an open question. It is known however, that toxic substances inhibit defence system in fish which makes them more susceptible to parasites. The following quotation, however circumstantial the connection may be, will serve as a reminder. A recent scientific cruise examining the health of fish from the sea, where major fishing grounds exist, found the following:

"From the outside all the fish looked healthy enough. But when the fish were sectioned every liver was infested with parasites. In many cases the liver had been all but completely consumed. How had the fish stayed alive? Some fish possessed a bloody liver. In others the liver was smaller or larger than normal. Some livers were green. All were discoloured. None were normal. None were healthy ..." (Karakoç and Doran, 1995).

6. Conclusions

The present state of coastal seas is a result of an increasing exploitation by people living on its coasts. The cheapest way toward the formulation of an optimum management of the coastal sea against pollution is through an appropriate modelling, experimental research and monitoring.

Today there exist software packages which may help in integrating the above three activities so that the optimum environmental management plan can be selected. The implemented procedures include estimation of the residual current field, estimation of an average concentration field, inverse (indirect) estimation of sources and construction of predictive models. Existing models can be used to assess effects of various environmental management plans. Comparing the impact to the level of financing required to implement each plan leads to the optimum plan. This means that necessary procedures to perform a reliable cost/benefit analysis are available.

Acknowledgments

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(14)

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Demonstration of the software package RECON

THE OBJECT OF STUDY: A bay on the Adriatic coast.

The community is interested to finance clean-up of the bay. However, since no one has conclusively shown how much is each polluter contributing to the total, negotiations about the share of each polluter in financing the clean-up are stuck.
In addition, community has agreed that all locations in the bay are not equally important, so if pollution from a source does not reach sensitive places, it will be taxed less.
Hence it would be necessary to decompose known concentration at a sensitive location into contribution by each source. Assuming the results could be justified, following table would solve the problem:

Name of the source	In % of the total concentration at the location Lx L1	L2	L3
Source 1	?	?	?
Source 2	?	?	?
etc.	...	...	...
Total	100	100	100

Table 1

PREVIOUS WORK

The community has identified locations of some sources but not all. It is suspected that apart from point sources there exist diffuse sources. The intensity of sources is not known.

The community has financed measurements of heavy metals in water and sediment. Measurements have shown that concentrations are indeed elevated.
From data and their interpretation one were unable to fill Table 1.

PROBLEMS

Prior to using RECON, we tried hard to get reliable direct estimates of sources since, when possible, it is easier to estimate sources directly then to compute them from concentrations of a pollutant in water. Using direct methods, we succeeded to estimate the intensity of one source.

The remaining sources were unknown.

In using RECON, our tasks can be stated as follows:

Reconstruct movement of water in the bay (the current field) as a basis to deal with concentrations.

Using objective analysis get the concentration field from data in order to find locations of unknown sources.

Use all data available to automatically construct the transport model, obtain the best estimate of the remaining sources and display the best concentration field.

Usually we have data about concentration in water on several locations in the bay, but since these are unreliable, we use data in sediments, and rescale the concentration field to the mean value in water.

Decompose the total concentration field into fields caused by one source. As a result fill the table 1.

Predict concentration fields which would result from implementation of a series of management plans so that community managers can choose the plan which has the highest benefit/cost ratio. Such a plan is called optimal.

For this demonstration let us take the example of total lead (Pb) in water.

EXISTING DATA

a) Geometry of the bay.
b) Measurements of currents on one station.
c) Few data on concentration of Pb in water.
d) Concentration of Pb in sediments on 12 stations in the bay.

RUNNING RECON

Figure 1

The shape of the Punat Bay with one island inside. We select the region to be processed by putting a frame around it. Moving the cursor to water, we press <F> key and the subregion gets filled. Only the filled part will be processed.

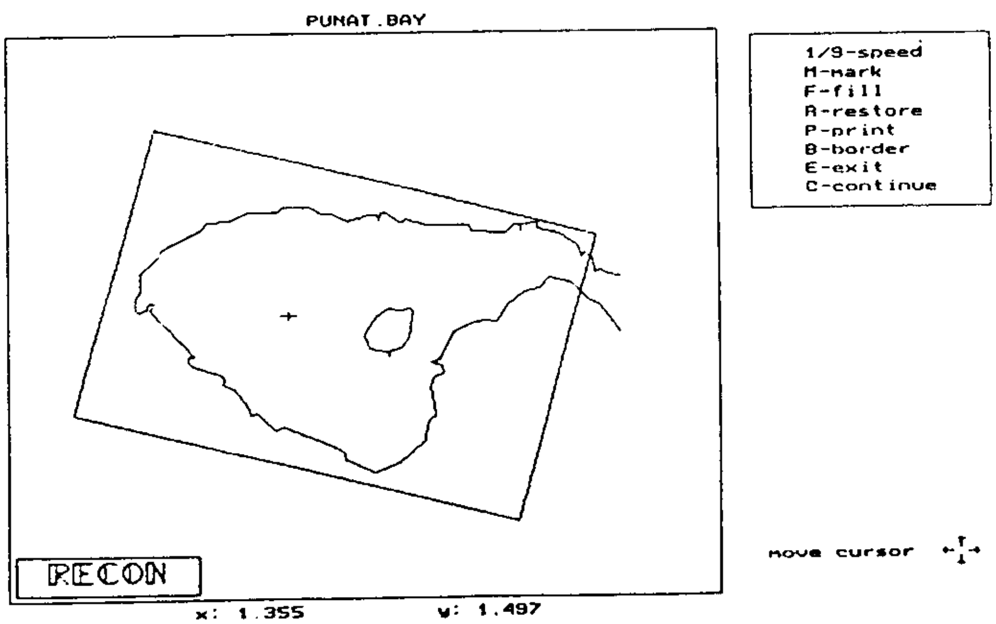


Figure 2 RECON constructs the numerical mesh and identifies open boundaries. Note the open boundary on the right side. Boundary condition is entered by filling the questionnaire in the window.

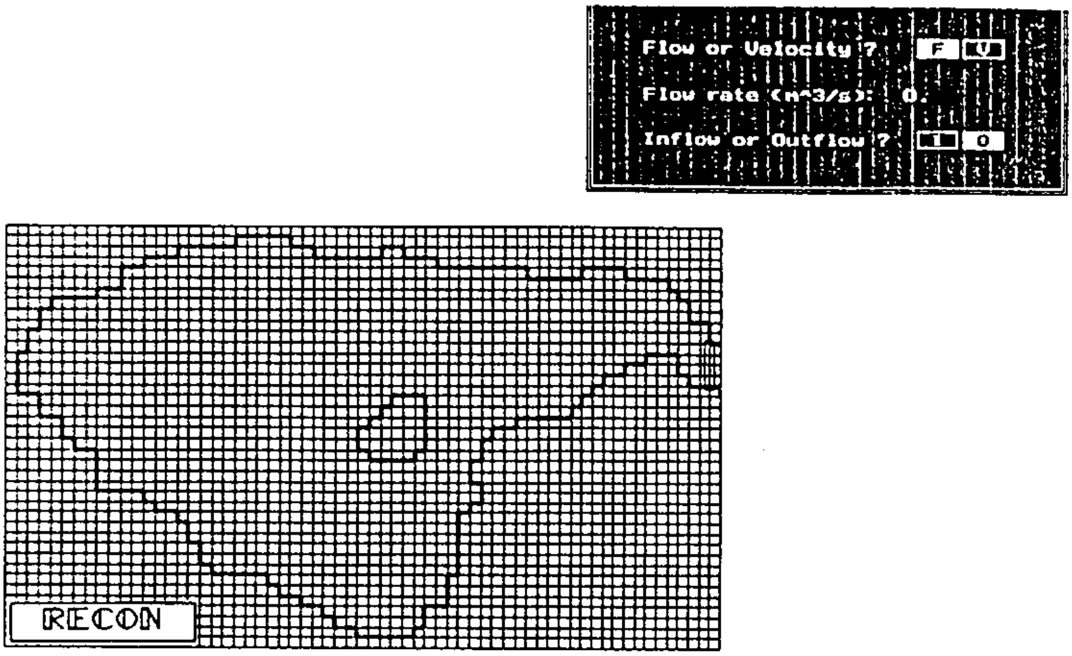


Figure 3

RECON's interpretation of the existing data. For illustration, more data is displayed than we actually have. Only the current measurement near the island is used in this case study. By pressing <C> RECON comes up with the next figure.

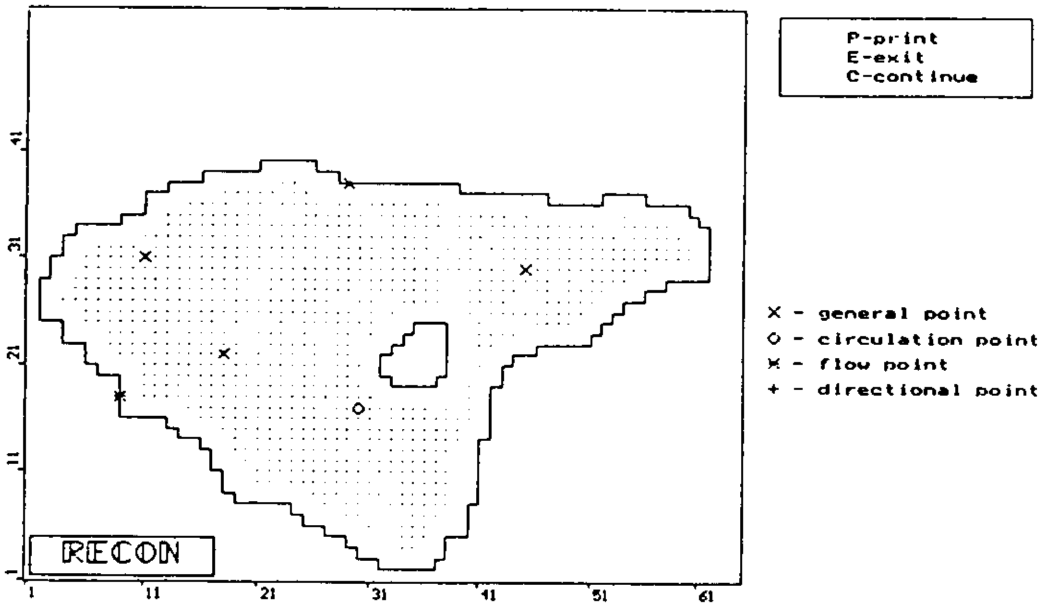


Figure 4

This is the sought current field. By pressing <C>, RECON asks whether we want to investigate this field. If we answer with <Y>, figure 5 is displayed.

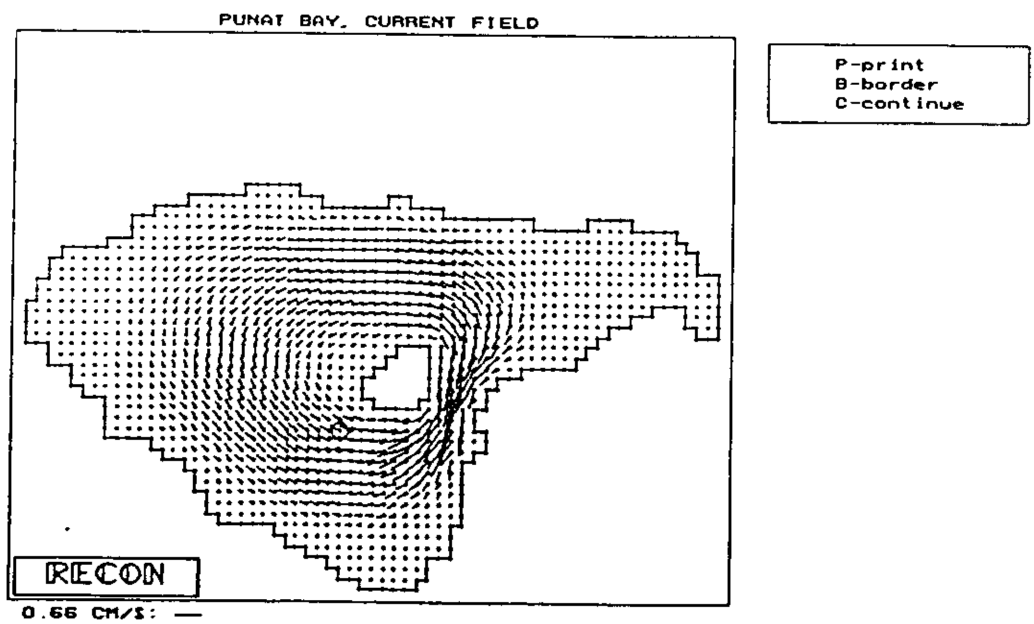


Figure 5

Using cursor keys one moves the cursor (black dot) around and reads the intensity of current (v) in x and y direction on the right side.

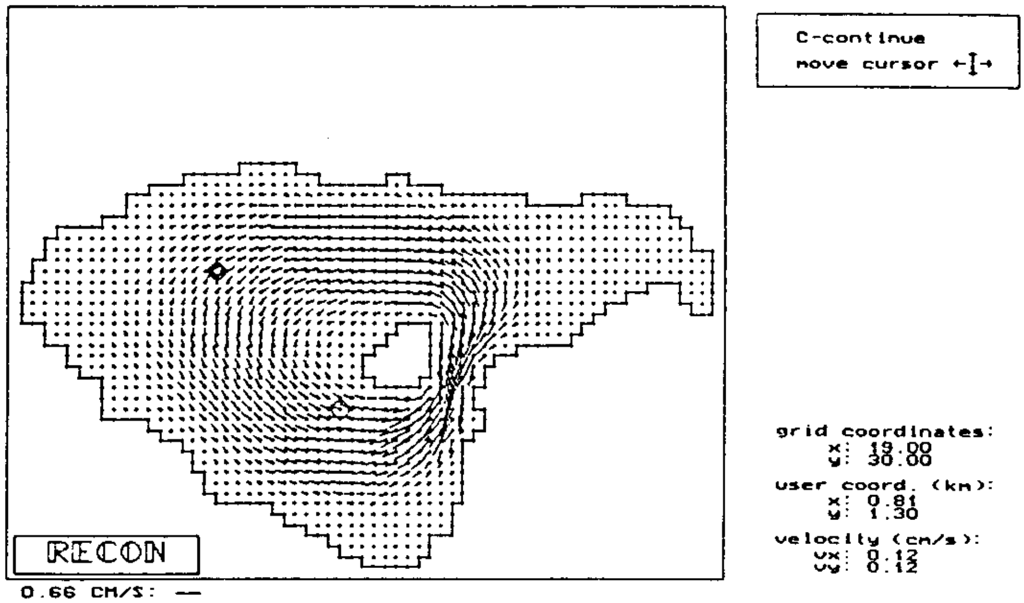


Figure 6

The display is used to omit or change velocity at a measurement station and recompute the current field. The facility is used to investigate the importance of each measurement station i.e. the dependence of the current field on data from each station.

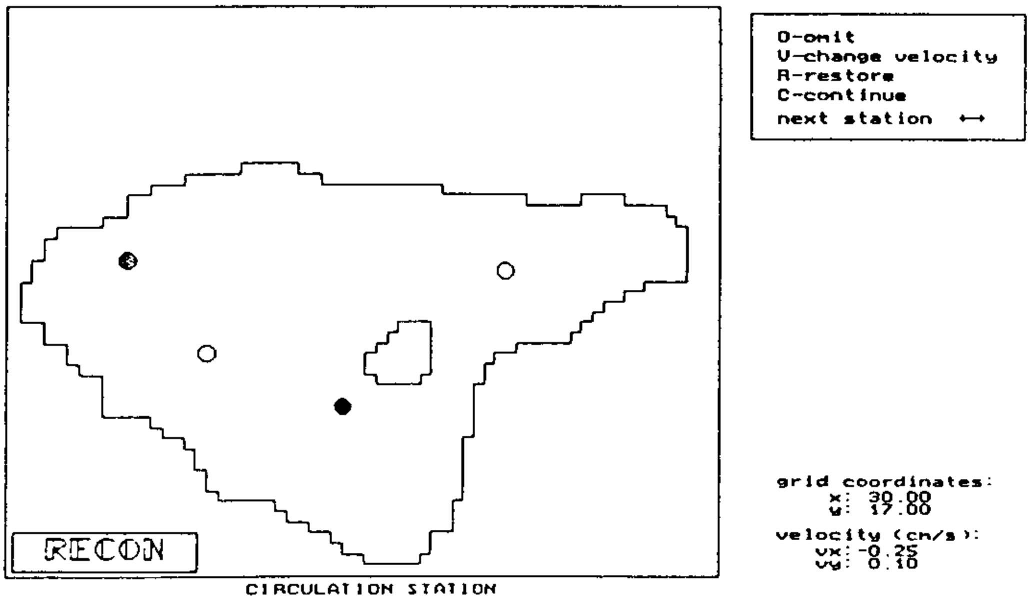


Figure 7

Reconstructing the concentration field. The display is used to enter open boundary condition. Possible conditions are found in the window.

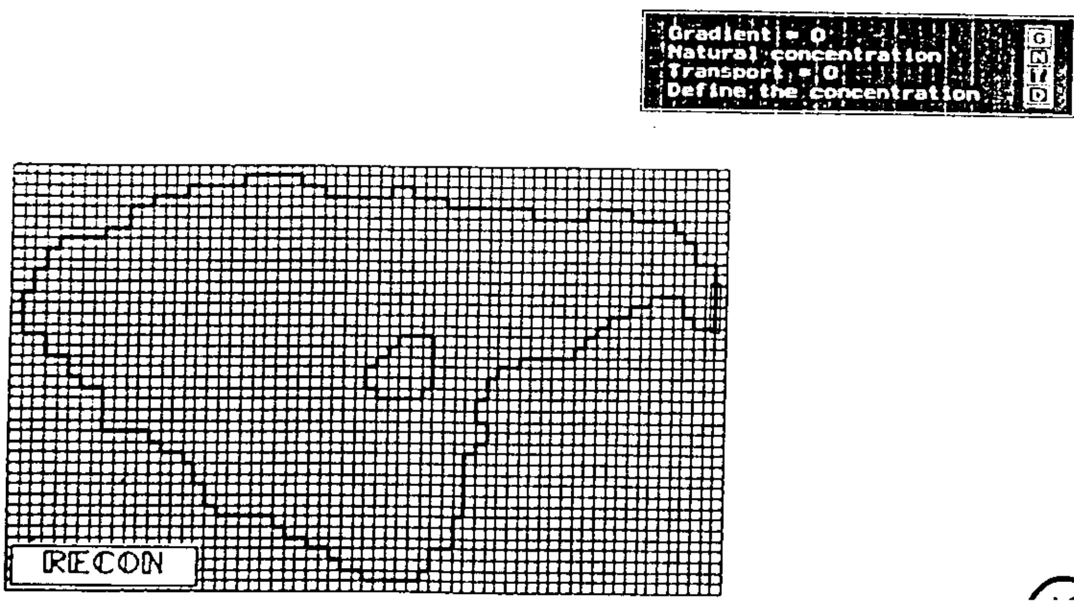


Figure 8

All accepted data on concentration is displayed. User carefully checks for presence of all hypothesized sources and measurement stations. Following this figure RECON computes the total concentration field.

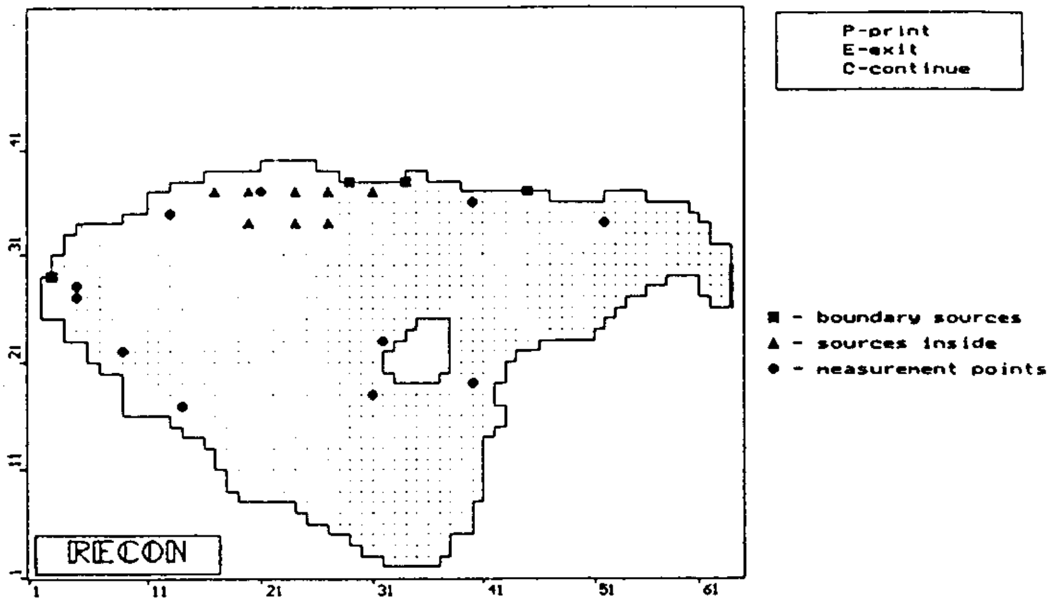


Figure 9

Total concentration field of Pb in water. Legend for isoconcentration lines is displayed on the right. In this example we are not using values from the actual case study. Displayed values are higher than in reality.

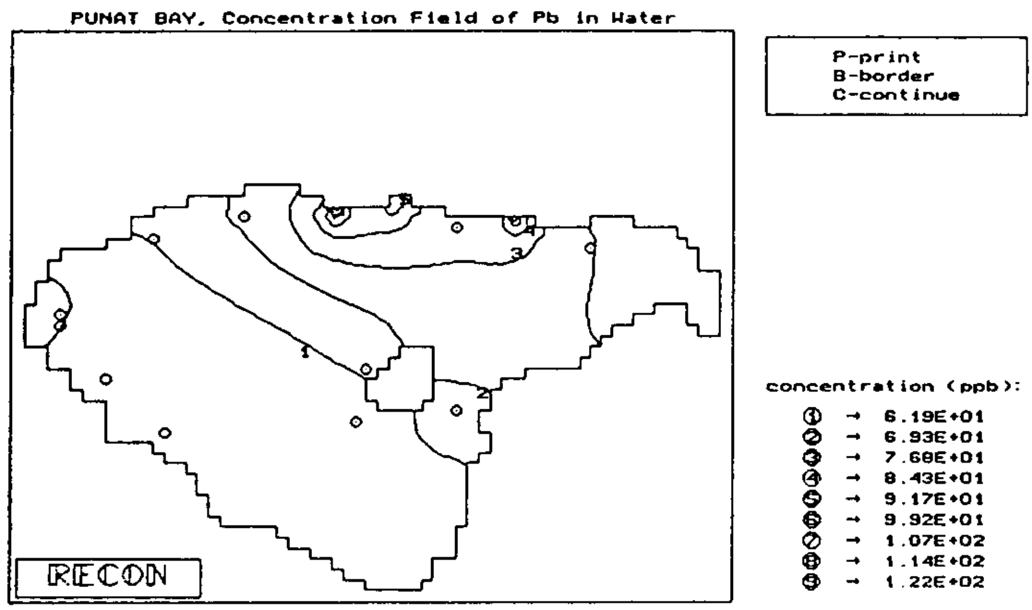


Figure 10

Concentration field may be viewed by moving the cursor (black point) within the bay. Concentration at the cursor position is displayed on the right side.

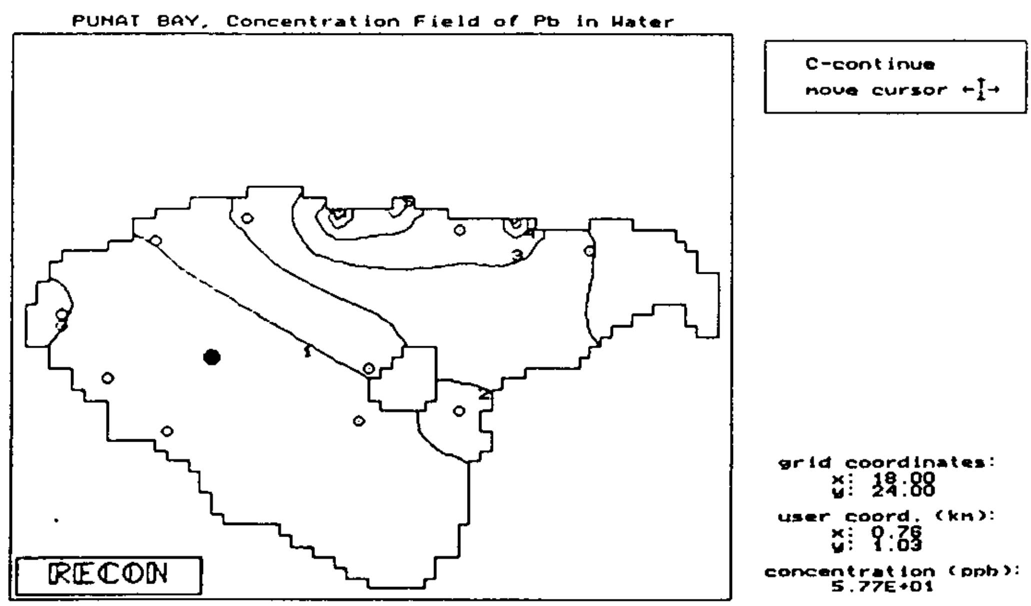


Figure 11

Following a request by the user, RECON can decompose the total field into components which would result from a single source. The figure, shows the concentration field resulting from the marine only. User can request isolines, view the field or display color illustration. On a black and white monitor, "color" illustration would look like this picture.

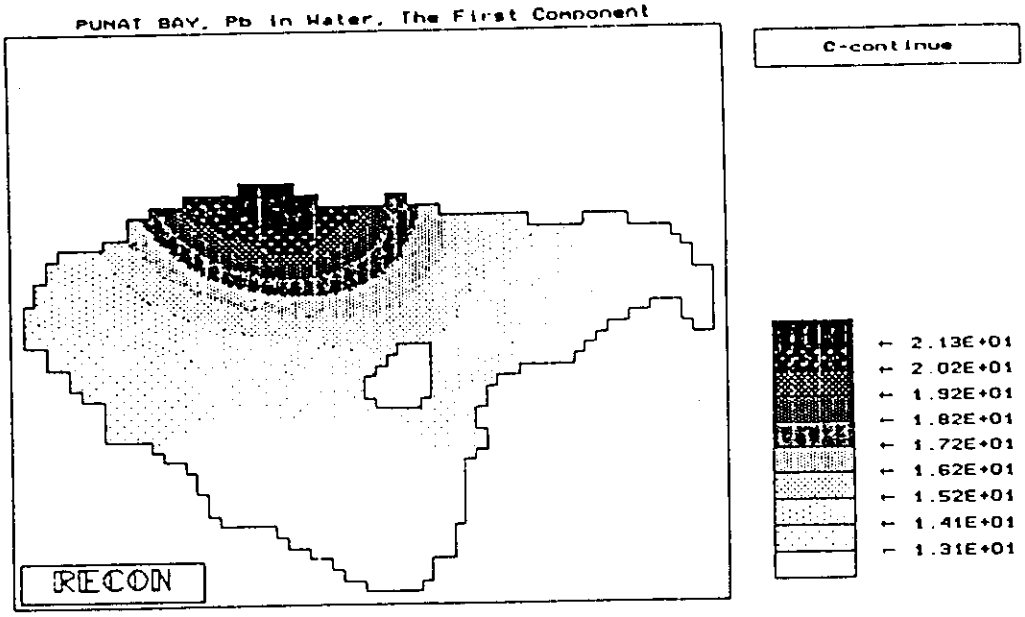


Figure 12

The concentration field due to shipyard 1.

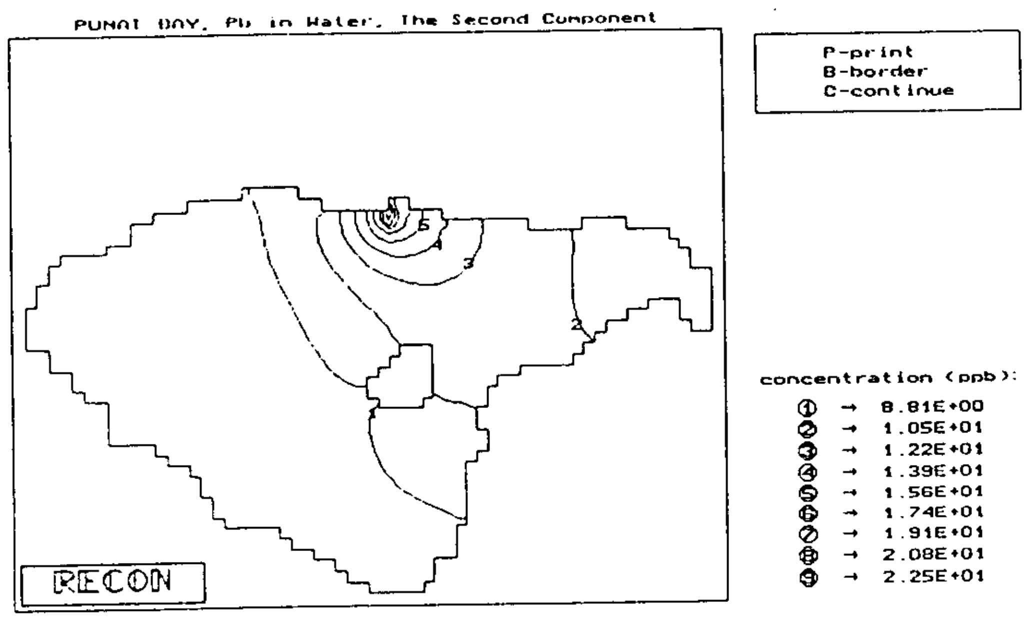


Figure 13

Zooming into a part of the region may be requested. Displayed is the region near the source from the previous picture.

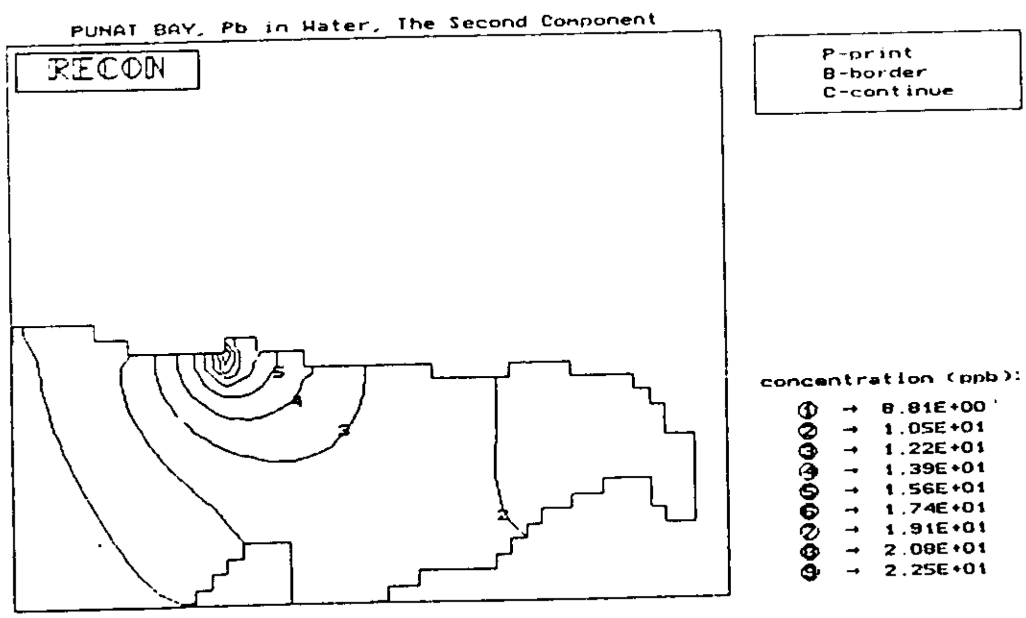
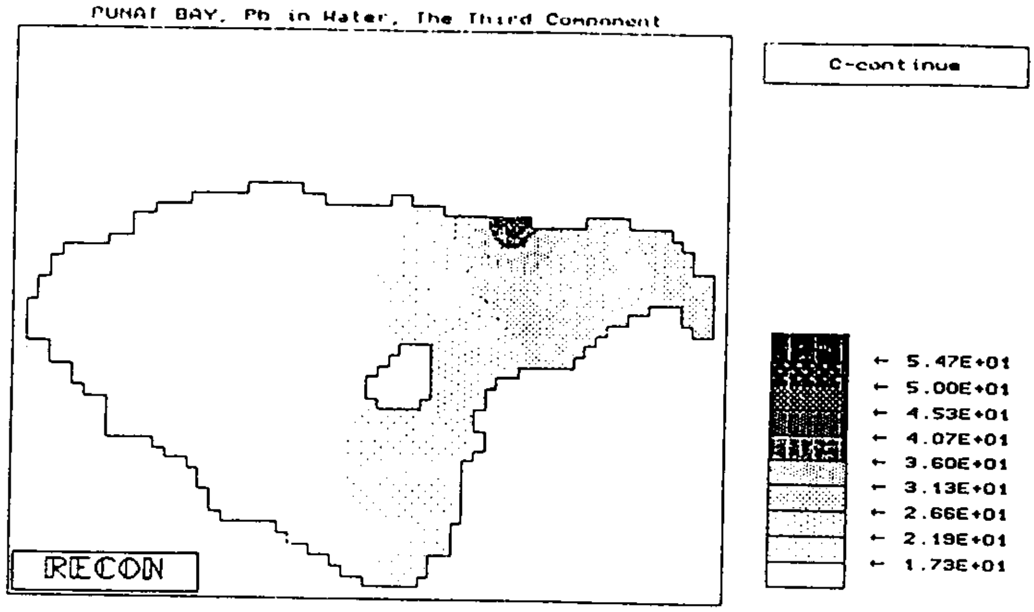


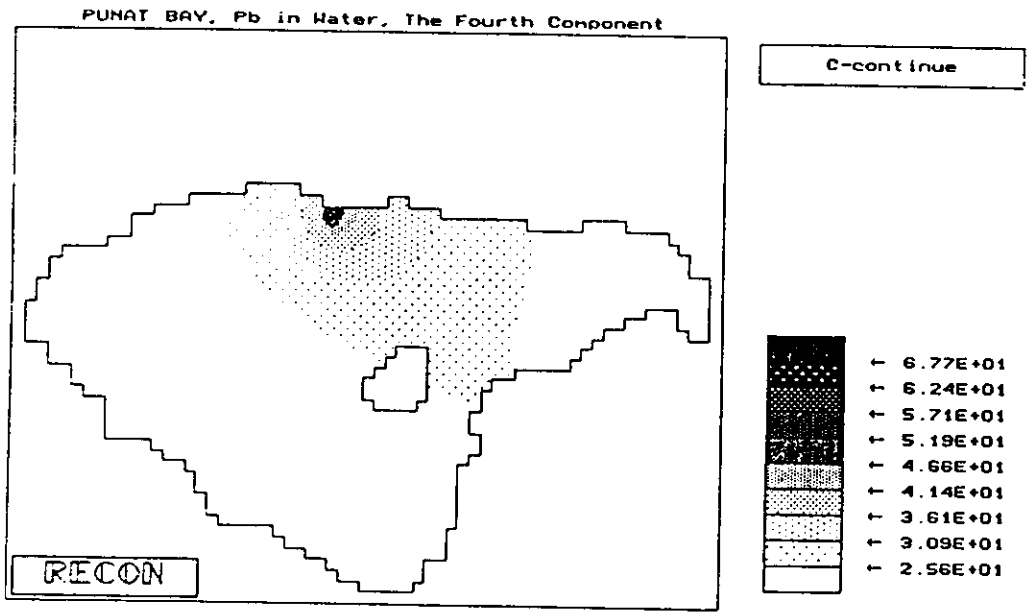
Figure 14

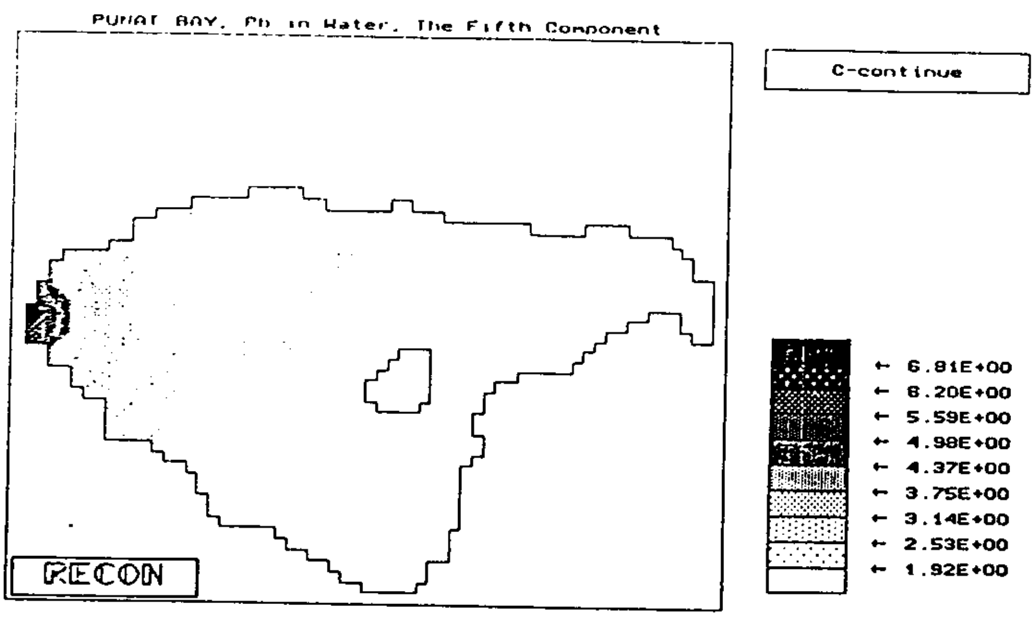
Figure 15

Figure 16

These figures contain fields due to collector, shipyard 2 and an unknown source at the beach, respectively. Following the discovery of the source at the beach, it was found that it probably originates from the uphill residential community. Pollution moves through the soil and comes out as a diffuse source at the beach.







COMMENTS

Prior to giving the above results, RECON has constructed and optimized a transport model. The model is ready to give predictions following a change in location and/or intensity of any combination of sources. In addition, a complete mass balance has been computed (the intensity of each source, the flow of substance through the open boundary, extinction rate and flux to sediments). Given are also computed and measured values at measurement stations and a measure of goodness of fit.

All of the above results are stored in INFORM.AUX file which may be printed as a permanent record of a session.

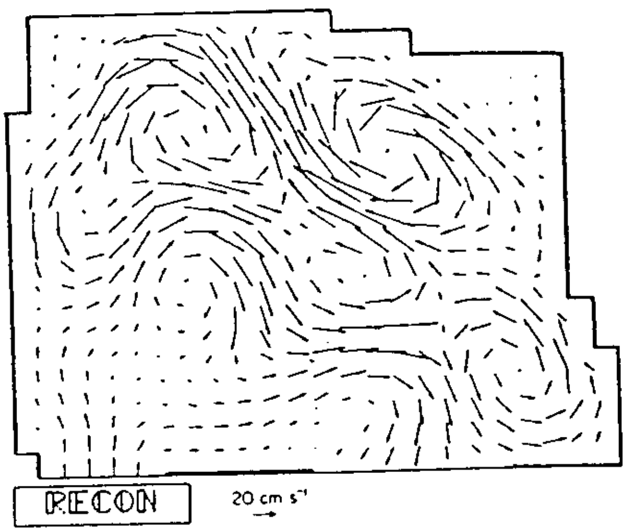
From information in the INFORM.AUX file one obtains directly:

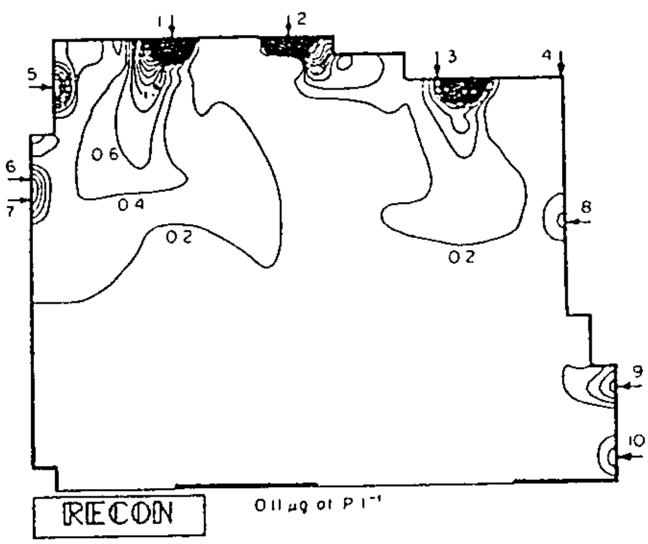
Source in % of total Pb	marine	collector	shipyard 1	shipyard 2	beach
	17.1	26.8	16.6	24.1	15.4

Table 1 can easily be filled by moving the cursor to a desired location(s) during display of fields from Figures 11, 12, 14, 15 and 16.

End R E C O N Demo

Results of another case study:





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