Integrated System for Ground Water Pollution Analysis

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ABSTRACT; The impacts of socio-economic development on soil- ground water pollution are investigated by referring to several countries which face related problems. The study suggests an analysis system which integrates several models with a GIS as a core. These models function together to simulate ground water pollution as a consequence of development policies. As a prelude to system development effort, a prototype model for examining the dispersion of pollutants into soil-ground water is developed. An example analysis is demonstrated to show the use of the model.

KEYWORDS; Ground Water Pollution, Socio-economic Development, Pollutants Dispersion

1. Introduction

Among the different available sources of water, ground water represents 68.4 percent of the total fresh water resources on earth. Current trends of socio-economic development are proved to result in not only positive impacts but also adverse consequences. A common negative impact is increased waste production and consequent ground water pollution. This results in health problems and loss of a scarce resource for fresh water which will eventually hinder further development. Most of the countries, especially in developing regions, do not have effective solutions of these problems. Therefore, to pursue sustainable development, it is important to study the impacts of socio-economic development on ground water pollution and vise versa.

This paper firstly proposes a GIS-based integrated analysis system which can be implemented to examine the different aspects of the ground water pollution problem. The system starts with analyzing the impacts of socio-economic development on waste production, then examines how these wastes disperse into the ground water, and finally shows the reverse impacts of pollution on socio-economic development. Secondly, development and application of a pollutants dispersion model is discussed taking into account its role within the whole system.

It should be noticed, however, that our main emphasis in this paper is on the philosophy and the scope of a total analysis system rather than on a specific modeling technique for pollutants dispersion.

2. Mechanism of Ground Water Pollution

The general mechanism of soil and ground water pollution problem in the context of socio-economic development and population growth can be schematically represented as in Figure 1.

Within this mechanism, world population is rapidly increasing, with nearly 15 per cent of this increase taking place in developed countries and over 85 per cent in developing countries (as of 1991/92)[1]. At the same time, economic, industry, and agriculture development are being improved by implementing modern technologies. This results in an income increase especially in developed countries.

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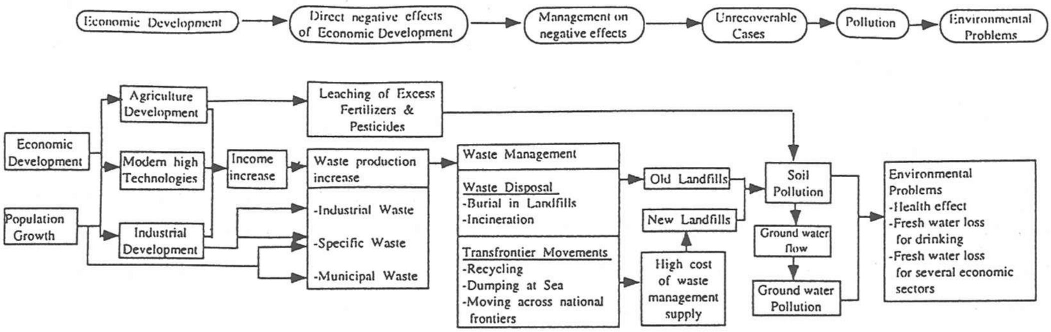


Figure 1. General mechanism of soil and ground water pollution problem due to socio-economic development

To cover required food supply for this increasing population, modern high-technology has been developed in commercial agriculture and intensive livestock farms. Chemical fertilizers, manure and pesticides, are added to soil to maintain and increase its productivity. However, this also results in many additional undesirable side-effects such as accumulation of nitrate, chlorine and others in the soil and ground water. Evidences of such a phenomenon were observed in several countries such as Denmark, Netherlands, Canada and so on. For example, Figure 2a shows a generally increasing application rate of nitrogenous fertilizer in some OECD countries. Evidence of a consequent increase in nitrate concentration level in ground water is depicted in Figure 2b talking Denmark as an example.

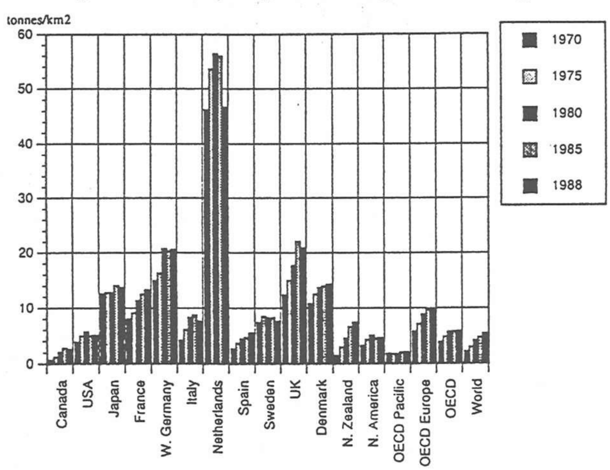


Figure 2a. Nitrogenous fertilizer use in some OECD countries, 1970-88[2)]

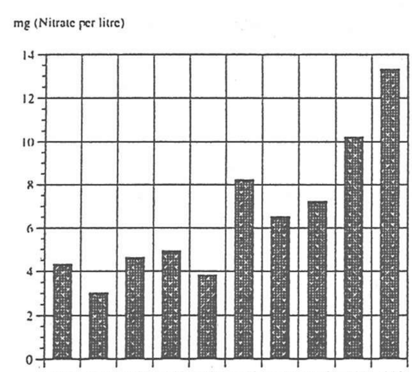


Figure 2b. Nitrate levels in ground water in Denmark, 1940-85 (Average values for 5-years periods)[3)]

On the other hand, higher income, population growth, and industrial development bring an increase in domestic consumption and thus more waste generation. Disposal of waste is one of the main sources for soil and ground water pollution. Burial of waste in municipal landfill sites is believed to be the easiest and most economical way. However, in the long run, old landfill sites take the form of "problem sites" with risks not only to ground water but also to the health of those who live nearby. There are old hazardous waste disposal sites which need to be cleaned up immediately in the United States, W. Germany, etc. Failure in supporting proper waste management because of the lack of budget or technology limitation, it will cause serious public health problems.

All the above consequences of development and population growth eventually lead to severe pollution of ground water resources and, thus, loss of fresh water for daily life and for agriculture and industries. On the contrary, to further support the increasing population and economic development, we need more qualified fresh water. Fresh water withdrawn by OECD countries increased from 830 km^3/year in the 1970s to over 900 km^3/year in the 1980s[2]. Moreover, given that some countries heavily rely on ground water as a source for fresh water, such as Canada where ground water represent 70% of water resources[1], the impact of this damage can be considerably great in such countries. Figure 3a shows the trend of water withdrawal per capita in some OECD countries while Figure 3b depicts the heavy reliance on ground water as a source for drinking water supplies.

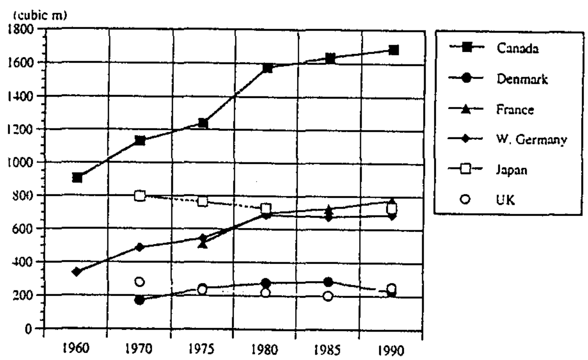


Figure 3a. Water withdrawal per capita in some OECD countries, 1960-1990[2)4)]

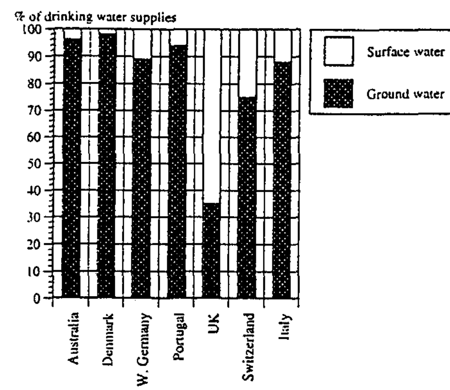


Figure 3b. Ground water resources used for drinking water supplies in some Europe countries, 1988[5]

3. Study Approach and Objectives

As discussed above, socio-economic development results in serious adverse consequence on ground water quality. However, since economic development cannot be renounced, ground water pollution should be either prevented or water quality should be recovered. For the latter alternative, there are several soil and ground water remediation technologies being developed and attempted by many industrialized countries[1) 6) 7)]. However, performance evaluation of these techniques suggests that cleaning up polluted ground water to meet standards cannot be achieved at a vast majority of the contaminated sites. Moreover, because of the high cost required for cleaning up polluted sites, it is almost impossible for most of the developing countries to adopt such technologies.

Therefore, preconsidering the source of pollution, characteristics of pollutants flow in ground water, and possible socio-economic effects of water pollution is a better way to pursue sustainable development.

Having realized this fact, we strongly felt that the existing trend of handling the issue either by implementing dispersion models to predict pollutants flow in ground water or by implementing environmental models to predict the amount of pollutants is not enough for clarifying the divers aspects of the issue. Rather, developing an integrated system which couples the above two types of models along with impact evaluation module would be more logical approach to analyze policies. To tackle the problems which would arise from dealing with diverse data types, a GIS system can be implemented as the core of this system through which data can be integrated and passed to each component of the system. A flow chart of the proposed system is shown in Figure 4.

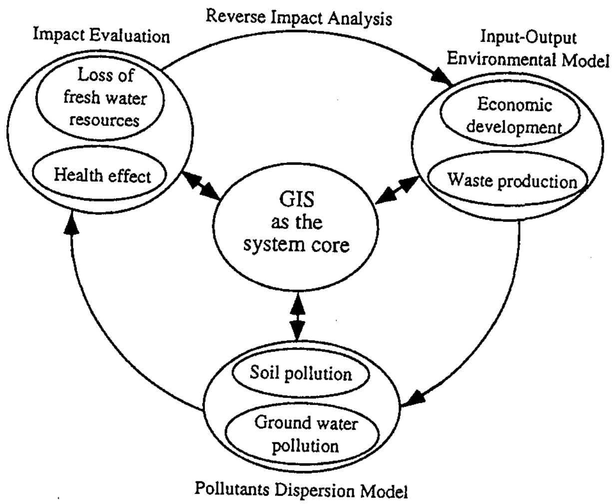


Figure 4. Elements and logic flow for the proposed system

As shown in the figure, the proposed system is composed of three main components and has GIS as a core. The function of the GIS is to facilitate data exchange among the different components and integration of diverse data types. The first component is an adapted Environmental Input-Output Model which is based on the interrelationships of production activities in modern economic systems. To include environmental concerns in the conventional input-output framework, modified input-output coefficients describing the emissions rates of different types pollutants caused by the production activities of each sectors in the economic system will be used. Also the I-O table for this analysis includes a sector responsible for abatement of pollutants. Using this model, effects of the change in production/consumption level, as a result of population, technology, and income trends, on waste production can be studied. The second component is a Pollutants Dispersion Model which receives the outputs of the first component through the GIS along with soil characteristics data. This model produces outputs which describe soil and water pollution within a study area. The last component is an Impact Evaluation Model which predicts possible health risks, loss in soil productivity, and loss of fresh water resources based on outputs of the previous model. This model can also analyze the reverse impacts on the socio-economic conditions of the study region. The overall system can be implemented for the evaluation of alternative development policies.

In this paper, we present a prototype 2D model for pollutants dispersion simulation as a prelude to system development effort. In later stages of system development, this model is intended to be upgraded to develop 3D modeling.

4. GIS-Based Analysis System for Pollutants Dispersion

4.1 Outlines of the system

The developed system encompasses an advection-dispersion model for pollutants which is based on FEM (Finite Element Method) coupled with a GIS. The advection-dispersion model gets the geotechnical data of any spatially selected points automatically from the Nagoya subsoil map stored in the GIS. The system also contains a module called AUTOMESH which was developed for dividing the expected influence space of pollutants flow and dispersion into mesh based on soil stratification. The output of this module along with the other data retrieved from the GIS are then passed to a code for FEM analysis. With this configuration, the required analysis can be easily handled.

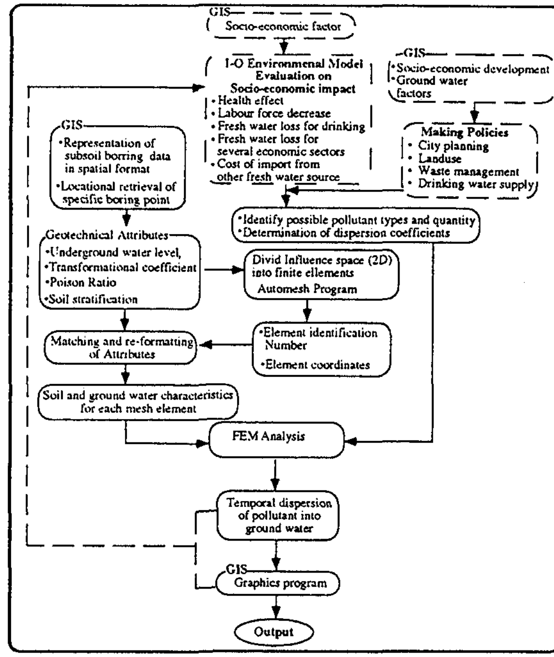


Figure 5. Outlines of the Pollutants Dispersion Model

Figure 5 shows a schematic representation of the system outlines. Development of the system started with arbitrarily choosing a study area with available subsoil information. Boring data, including both location and attributes, are then stored as a map in a GIS. For any study location, dominant subsoil characteristics can be retrieved by simply indicating this location. Based on the extent (width and depth) of the expected influence space of an assessed pollutant source (using I-O model and GIS) and the stratification at that location, the AUTOMESH module of this prototype is implemented to divide this vertical 2D space into finite elements with equal widths and varying depths based on the depth of each soil stratum. Attributes, both locational and subsoil characteristics, are then attached to each finite element and passed to the FEM module. This modules caries out the final analysis in the form of pollutant flow and dispersion into the influence space with time. The results are then passed to graphics program for display. These predicted results will be passed to a subsystem to evaluate socio-economic impacts and will be utilized for management policies for waste disposal or land use, etc.

The main advantages of this system can be summarized as follows: 1) having GIS as a core of the system, the time and effort required for preparing inputs to the FEM are minimized, 2) using this system, it is possible to estimate the environmental impacts of pollutants disposal and leak by referring to other types of information stored in the GIS, such as population distribution for example, and 3) the whole analysis can be spontaneously handled within one computer system (UNIX workstation for our system).

However, more realistic results can be obtained if the third dimension of the influence space is considered. Therefore, our next step will be to upgrade this system to a 3D model. In this case, the role of GIS will be even more crucial.

4.2 Outlines of the FEM model

In soil, material movement with adsorption to soil surface is represented by:

$$\frac{\partial C}{\partial t}=\frac{1}{R_d}\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right)-\frac{1}{R_d}\frac{\partial}{\partial x_i}(Cu_i)+W_c \tag{4.1}$$

where,

C: Fuse material density,
R_d: Retardation factor,
D_{ij}: Dispersion coefficient,
u_i: Velocity of water flow, and
W_c: Supply of fuse matter.

And ground water movement obeys Darcy's law which can be represented as:

$$s\frac{\partial h}{\partial t}=\frac{\partial}{\partial x_i}\left(k\frac{\partial h}{\partial x_j}\right) \tag{4.2}$$

where,

h: Water head potential,
k: Permeability coefficient, and
s: Storage coefficient.

By combining Equations (4.1) and (4.2), and using FE descretization, the following coupled equation system can be obtained:

$$\begin{bmatrix} \boldsymbol{M}_{HH} & 0 \\ 0 & \boldsymbol{M}_{CC} \end{bmatrix}\begin{Bmatrix} \boldsymbol{H} \\ \boldsymbol{C} \end{Bmatrix}+\begin{bmatrix} \boldsymbol{K}_{HH} & 0 \\ 0 & \boldsymbol{K}_{CC} \end{bmatrix}\begin{Bmatrix} \boldsymbol{H} \\ \boldsymbol{C} \end{Bmatrix}=\begin{Bmatrix} \boldsymbol{Q} \\ \boldsymbol{W} \end{Bmatrix} \tag{4.3a}$$

$$\begin{aligned} \boldsymbol{M}_{HH} &= \int_V S\boldsymbol{N}^T\boldsymbol{N}\,dV \\ \boldsymbol{M}_{CC} &= \int_V \boldsymbol{N}^T\boldsymbol{N}\,dV \\ \boldsymbol{K}_{HH} &= -\int_V k(\nabla\boldsymbol{N})^T(\nabla\boldsymbol{N})\,dV \\ \boldsymbol{K}_{CC} &= \int_V(\nabla\boldsymbol{N})^T\frac{1}{R_d}\boldsymbol{D}(\nabla\boldsymbol{N})\,dV+\int_V\frac{k}{R_d}(\nabla\boldsymbol{N})^T(\nabla\boldsymbol{N})\boldsymbol{H}\boldsymbol{N}\,dV \end{aligned} \tag{4.3b}$$

where,

$\boldsymbol{N}$: Shape function matrix,
$\boldsymbol{H}$: Potential vector of panel point head,
$\boldsymbol{C}$: Density vector of panel point,
$\boldsymbol{Q}$: Flow velocity of panel point, and
$\boldsymbol{W}$: Material input vector of panel point.

In Equation (4.3b), the second term of K_{CC} represents the coupling effect. Equation (4.3) can be solved by the θ-method:

$$[C+\theta\Delta tK]X^{(n)}=(1-\theta)\Delta tY^{(n-1)}+\theta\Delta tY^{(n)}+[C-(1-\theta)\Delta tK]X^{(n-1)} \quad (4.4)$$

where,

$$C=\begin{bmatrix} M_{HH} & 0 \\ 0 & M_{CC} \end{bmatrix},\ K=\begin{bmatrix} K_{HH} & 0 \\ 0 & K_{CC} \end{bmatrix},\ X=\begin{Bmatrix} H \\ C \end{Bmatrix},\ Y=\begin{Bmatrix} Q \\ W \end{Bmatrix} \quad (4.5)$$

5. Example of Analysis

The developed system was implemented in a simple case study to illustrate its use and possible outputs which can be obtained. The study simulates the leakage of a pollutant from a factory located in Nagoya city, Toyota-cho, Minami-ku. For the analysis, the following assumptions were made: 1) we consider unconfined ground water with saturated layer, 2) water flow obeys to the Darcy's law and the water heads at both sides of the study area are given by the data from GIS, 3) ground water and pollutants do not infiltrate into deep soil layers where impermeable layer exists, 4) the pollution source is located at the center of the influence space, 5) the pollutant has the same specific weight as water, and is not absorbed on soil particles, 6) concentration of the pollutant is initially 100% at its source and 0% in the rest of the influence space, and 7) analysis time interval Δt is one day. Parameters used in the analysis are presented in Table 1.

5.1 Soil characteristics

Dominant soil characteristics of the influence space was retrieved from the GIS system by interactively pointing at the study location on a map display of the study area. Stratification at this space is as follows: Nobi formation exists in upper layers at depth 2m to 8m, while Atsuta formation is dominant at deeper layers. In these formations, silt layers with low coefficient of permeability exist at depths 8.0-8.8m and 15.1-15.6m. Based on this formation and the above assumptions, it can be said that pollutants may spread easily to a maximum depth of 8.0m in the unconfined layer. As for ground water level, the left boundary of the influence space had a higher water level. Therefore, flow of water is assumed to be from left to right. Some necessary characteristics of soil which are not available in our soil data base, such as poison ratio and void ratio, were assumed based on available values obtained from the literature [3)4)5)]. As shown in Figure 6, the influence space (taken to be 40m x 20m) of an assumed pollutant source at point 'e' is then divided into finite elements based on the dominant soil characteristics. The FE model is presented in Figure 6 together with the boundary conditions. In the figure, "third boundary condition" means that the pollutant flux caused by dispersion is proportional to the difference of the densities at both sides of the boundary, and it is represented as:

$$D_{ij}\frac{\partial C}{\partial x_j}n_i=\gamma(C-C_0) \quad (5.1)$$

where,

n_i: Outward normal,

C_o: Density at exterior of the boundary, and

γ : A constant, which we set as $C_o=0$ and $\gamma = 1$.

5.2 Analysis of the study area

Assuming a leakage of the pollutant, Figure 7 shows the distribution map of pollutant concentration within the influence space after 20, 40, 100 and 200 days of the leakage. In the figure, numbers on lines represent the percentage of the pollutant concentration in the ground water.

In Figure 7.a, the pollutant spreads out from the center of the source. When pollutant reaches the impermeable silt layer at 8m depth, it flows horizontally rather than vertically. Because ground water flows from left to right, the pollutant also spreads faster towards the right side. In Figure 7.b, after 40 days, the 20% concentration line reaches the right boundary of the influence space while the 10% concentration line does not reach the left boundary of the area. This shows the influence of advection on the spread of pollutants. In Figure 7.c, after 100 days, the pollutant spreads through the impermeable silt layer at 8.0-8.8m depths at the right side of the influence space. In Figure 5.d, after 200 days, the pollutants spread through the impermeable silt layer at the left side too. At that time, pollutants passes also through the second impermeable silt layer at 15.1-15.6m depths at the right side.

5.3 Impact on human health

The underground water pollution causes many socio-economic problems and is regarded as an external diseconomy. How to quantify the socio-economic problems as diseconomical impacts is the important subject to be studied. However, no effective method to break through this point has been established yet. Here, we attempt to make a direct estimate of the impact on human health by the underground water pollution by assuming that the pollutant has the same poisonous effect on human health as the Trichloroethylene (TCE).

The oral lethal dose of TCE for an adult is 857mg per 1kg body weight[8]. Therefore, for a person with 60kg weight, the lethal dose of TCE is 5520mg. Here we assume that such a person drinks 1.5 liters of ground water everyday withdrawn at two selected surface points (point 'a', 20m to the left of the pollutants source, and point 'f', 8m to the right as shown in Figure 6) after the leakage of the pollutants. Figure 8 shows the daily dose intake (Figure 8.a) and the cumulative dose (Figure 8.b). Generally, the figure shows higher intake of pollutant near its source. In Figure 8.b, after 100 days, the pollutant dose is 100g at point 'a', which is equivalent to lethal dose for 20 persons. After 200 days, the pollutant dose is 1000g at point 'f' which is equivalent to lethal dose for 200 persons.

After 20 days, the cumulative intake of TCE at point 'f' is 3 times higher than at point 'a' in Figure 8.b. Therefore it can be concluded that, as intuitively expected, health risk at the downstream of pollutant source is much higher than that at the upstream.

5.4 Other consequences

Beyond this above mention direct impact on human health, other consequences may follow. For example, productivity of the labor force exposed to this health hazard will decrease. Also such a polluted water source will ultimately have to be either cleaned or abundant. Added cost for either quality recovery or securing new sources for fresh water will result in increase in water charges. This will in turn reduce the purchasing power of consumers and outputs of industries. In severe cases, the whole population and economic activities will have to relocate to other places. Several forms of socio-economic impacts can result from possible combinations of such consequences and their interactions. To study such impacts and alternative counter measures, the proposed integrated analysis system is essential.

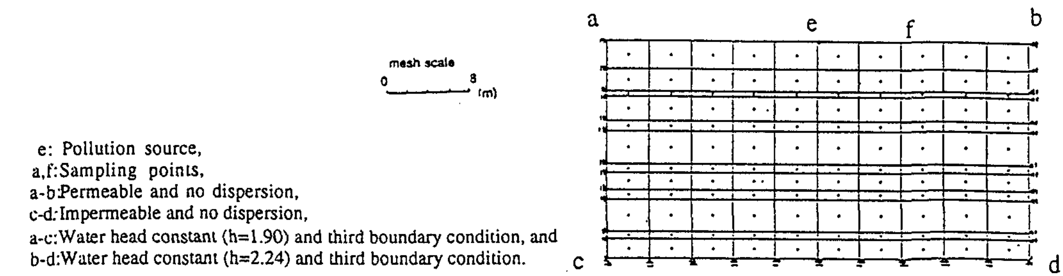
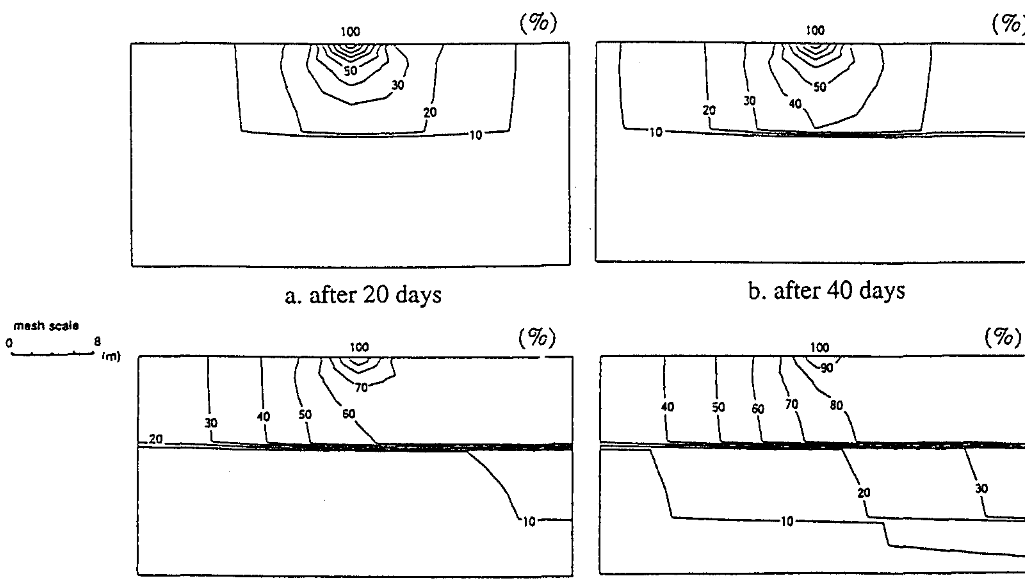


Figure 6. Influence space divided into finite elements



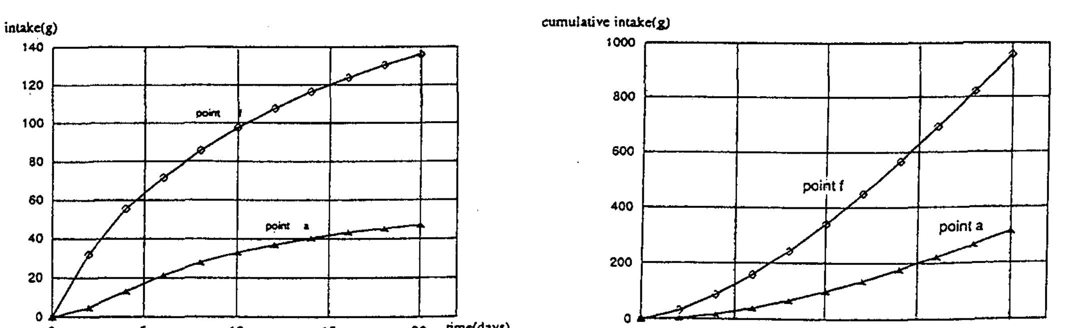
a. after 20 days

b. after 40 days

c. after 100 days

d. after 200 days

Figure 7. Distribution map of pollutant's concentration



a: daily dose

b: Cumulative dose

Figure 8. Intake of the pollutant

Parameters		units
Permeability	k	3.89×10^{-1} ~7.34×10^{1} (m/day)
Storage coefficient	s	0.0 (1/m)
Retardation factor	R_d	1.0 (no adsorption)
Dispersion coefficient	D_{ij}	D11 = 1.65×10^{-2} ~ 3.12, D12 = 0.0, D21 = 0.0, D22 = 1.65×10^{-2} ~3.12

Table 1. The parameters used in the analysis

6. Summary and Conclusions

This paper suggests that analysis of underground water pollution aiming at protection rather than quality recovery should consider the socio-economic aspects of the issue. In this context, a system for this analysis is suggested which encompasses the following components: 1) Environmental Input-Output Model, 2) Pollutants Dispersion Model, and 3) Impact Evaluation Model. GIS is proposed as the core of this system for data exchange and integration. Using such a system, development policies can be evaluated considering their possible impacts on ground water. The paper also presents a vertical 2D pollutants dispersion model as a prelude effort to system development. This model employs FEM techniques for studying flow and dispersion of pollutants into the soil and ground water. Through a simple case study, it is illustrated how the model can be used to predict the impact of pollutants disposal and leakage on ground water pollution and human health. In a similar way, the model can be also used, for instance, to evaluate the impact of extensive use of fertilizers or old landfill sites, etc.

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