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SEEPAGE OF CONTAMINANTS FROM WASTE CONTAINMENT

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An alternative approach to assist the environmental engineer in his care for the geo-environment is described in the stochastic continuum modelling of seepage from waste facilities. The prediction of seepage can be conducted for typical soil and protective layers around the containment to investigate possible contaminant movement under steady state conditions. An important parameter controlling the transport of these contaminants is the hydraulic conductivity of the soil. This paper looks at a fresh approach to the application of stochastic continuum modeling in generating hydraulic conductivity by kriged simulation. Flow and transport were computed numerically for the model. Results show that the approach is well suited for the simulation of seepage of contaminants around waste containment facilities.

INTRODUCTION

Flow and transport of contaminants including hazardous wastes are important current environmental issues. The variety and the amounts of hazardous wastes pose a significant challenge to environmental engineers and scientists in their efforts to preserve natural resources.

Several types of waste repositories have been utilized such as landfills, waste land-farms, containment ponds, containment in rocks, and deep underground injection. The containment method is one of the most common types of disposal system currently being used. It is important to monitor and control the leachate of toxic chemical fluids which may seep through the impoundment barriers and protective layers of liners of containment facilities. The integrity of these protective liners has to be monitored and maintained at all times. In determining their performance, the hydraulic conductivities of the various layers of soil are the main critical parameter to be considered. Kim et al. (1999) studied the economics of several alternatives to prevent groundwater contamination from a landfill site using a numerical model and hydraulic parameter measurements. The leachate flow system and the pollutant transport system around the landfill were analyzed using numerical modeling.

In this paper two approaches, namely the continuum classical model and the continuum stochastic model, were considered and compared in the determination of the distribution of contaminant concentration. Commercially available software was utilized as tools for the comparison. The SEEP utility was used to model the flow velocity for general seepage analysis of saturated and unsaturated flow for both the classical and stochastic approaches. The flow velocity was then determined using CTRAN to model the advection-dispersion process. The heterogeneous trend of hydraulic conductivity was modeled by SPLUS for the stochastic approach. For short periods of less than thirty (30) days, the results of the distribution of contaminant concentration were similar for both approaches.

GROUNDWATER TRANSPORT PROCESS

Simple cases of movement of groundwater are well described by Darcy's Law, but in order to handle the geometrical complexity of real systems, as well as the spatial and temporal variations of media properties, boundary conditions and variables, numerical techniques are required.

The system might only involve simple advection which is the movement of contaminants in porous media along with flowing groundwater at the seepage velocity. It might involve diffusion which is a molecular mass-transport process in which solutes move from areas of higher concentration to areas of lower concentration. Fatta et al (2000) demonstrated that an accurate and efficient computation of three-dimensional transport under advection-dispersion dominated conditions is feasible through extending the two-dimensional to a three-dimensional flow model domain. It might also involve dispersion which is a mixing process caused by velocity variations in the porous media. This could cause sharp fronts to spread out and can result in the dilution of the solute at the contaminant front. Variations in soil properties associated with differences in local geology need to be also appropriately modeled. Ibe and Njoku (1999) conducted geophysical and geochemical studies to investigate the migration of contaminants in groundwater around a landfill. Electrical resistivity soundings were conducted to determine the direction of contaminant transport, and surface and groundwater samples were collected and analyzed to determine the geochemical parameters. It was found from grain size analysis and litho-geophysical logs that contaminated leachates can migrate through the unsaturated zone into groundwater posing a threat to human health. A computer modeling study by Kho (2004) on groundwater flow and pollutant transport at a waste disposal site in Sabah, Malaysia also showed significant effects of pollutant migration from an abandoned waste disposal site to the surrounding land.

HYDRAULIC CONDUCTIVITY

Hydraulic conductivity is an important property in determining the behavior of groundwater and contaminant flow in soils. This parameter can be very difficult to measure and its value can vary depending on the methods of measurement being used. Due to difficulties and limitations in field instrumentation, the exact hydraulic conductivity field very often cannot be determined. There is therefore a necessity to model and estimate the hydraulic conductivity field. Most transport analysis studies use the average values and assume homogeneous conditions. This is the classical approach and it is an easy way to model the system, but field observations show that properties such as hydraulic conductivity for porous media are extremely variable. If the variations in the media properties are not taken into consideration, there can be appreciable discrepancies in the final flow results. The stochastic approach takes into consideration this variation in the values of hydraulic conductivity. In this study both approaches were used.

METHODOLOGY

Analytical tools for measuring and monitoring soil and groundwater quality are available. Gathering of data, however, can be costly and tedious. Computer models have been developed to minimize the need for field data. Physical as well as chemical properties of the contaminants and the properties of the soil media have to be well understood, as well as their interaction. With knowledge of these properties, several computer models are available which can be used and the results verified by field data.

The following are two methods which can be used to estimate the total hydraulic conductivity field from measured data:

(i) Classical Approach: use of the mean value of the measured data,

(ii) Stochastic Approach: use of simple kriging or use of indicator kriging.

Variogram

The variogram, $g(h)$, is a mean quadratic increment of Z between two points separated by distance h:

$$E[Z(x + h) - Z(x)] = 0$$

$$g(h) = \tfrac{1}{2} \operatorname{var}[Z(x + h) - Z(x)]$$

Kriging

Kriging is a method for optimizing the estimation of a magnitude, which is distributed in space and is measured at a network of points. Let $x_1, x_2, \ldots, x_n$ be the locations of the n points of measurement (x_i denotes one, two, or three coordinates of the point i and $Z_i = Z(x_i)$ is the value measured at the point i). Point estimation lies in determining the value of the quantity Z_0 for any point x_0 that has not been measured by continually modifying the position of the point x_0. It is thus possible to estimate the whole field of the parameter Z. A generalization of kriging also makes it possible to create an infinite number of conditional Monte Carlo simulations of the field Z i.e. different realizations of the map of Z, which is compatible with the measured data. These maps can be used to visualize the uncertainty of the estimation and as entries into stochastic models.

CLASSICAL APPROACH

Classical continuum models treat the soil as equivalent to an ideal porous medium. In its simplest form, the continuum approach calls for the assignment of average properties for relatively large blocks of the medium. This means that details of heterogeneity on scales smaller than the block size are lost. This is the easiest approach since it only uses the mean value and ignores scattering of the real hydraulic conductivity field. Errors in the calculated results can be anticipated, and they can serve as a comparison to the other two methods.

Figure 1 shows the transport model with the arrangement of soils in the case for the classical method where average values of hydraulic conductivity were used. The yellow color denotes a silt soil under unsaturated conditions whereas the green color denotes a silt soil under saturated conditions.

STOCHASTIC APPROACH

In the stochastic approach the spatial dependence between neighboring values of a random variable was defined in terms of a stochastic process model that defines the spatial correlation throughout the system. In this case the hydraulic conductivity might be considered to be the random variable with an associated probability density function at each point in the domain. A variogram could be generated to provide a measure of this spatial correlation by describing how sample data were related with distance and direction.

An artificial model could be built as a reference with different layers of soil, and the hydraulic conductivities for the various layers could be obtained by setting the measurement detection limit and performing Monte Carlo type stochastic simulations. Available computer programs with a comprehensive suite of tools designed for statistical analysis of spatial data were used to generate the spatial relationship. Various relationship models like the spherical model, the Gaussian and the exponential models are used. In this case, the exponential model is found to best fit the variogram.

For a rigorous numerical flow simulation, a number of realizations are usually created. The number of realizations is somewhat arbitrary. Cacas et al. (1990) created twenty realizations,

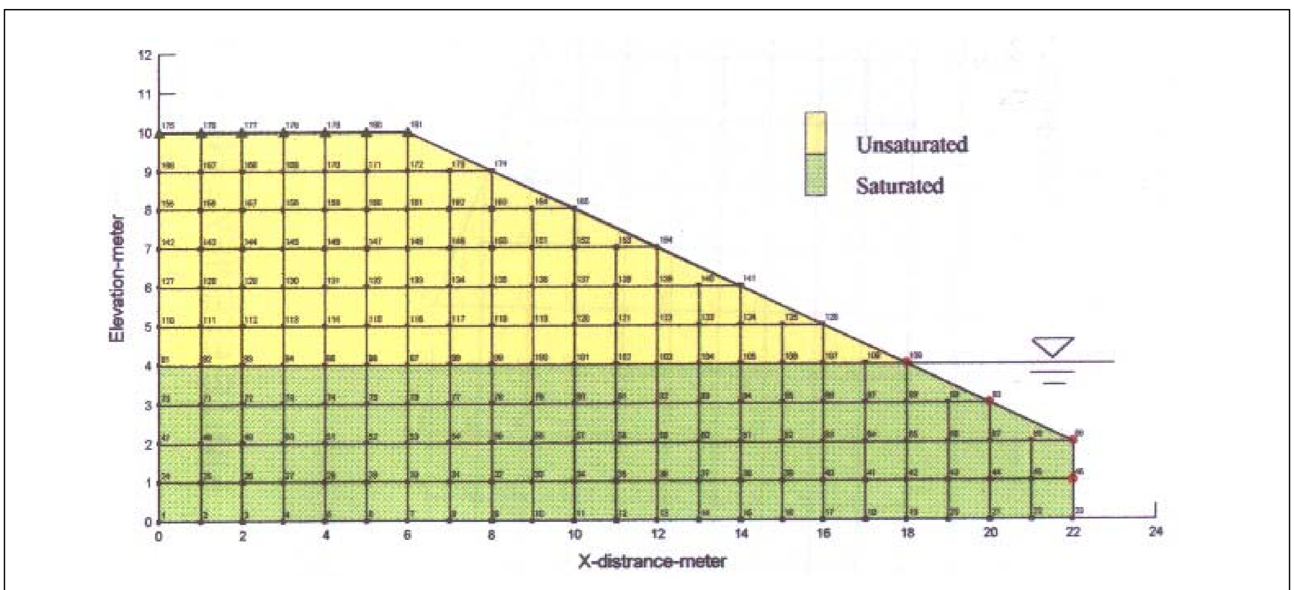

Figure 1. Arrangement of soil for the classical method.

Dverstorp et al. (1989) created thirty realizations, Ohnishi and Soliman (1996), and Ohnishi et al. (1997) created fifty realizations. Ismail (1998), Ismail and Hashim (2000) and Ismail et al. (1999) showed examples of a couple of realizations, which were generated and analyzed with respect to spatial and statistical properties.

Simple Kriging

This method considers scattering and spatial correlation of the hydraulic conductivity. The spherical function or any other suitable function can be fitted to the variogram to produce the realization of random fields. Using these properties, the overall hydraulic conductivity field can be estimated by a simple kriging method. Monte Carlo simulation may also be performed to repeat this process many times.

Even though this method does not consider values beyond the detection limit, a better result could be expected as compared with simple kriging. Several valid theoretical variogram models, i.e. models of a positive definite type, can be fitted to the experimental variogram, such as linear, spherical, exponential, or pure-nugget. The function used in this study is the exponential model with a value for sill or variance of the data and a value for range or separation distance beyond which there is no correlation between data. In the presence of a nugget effect, a nugget term is added to the equation. A nugget effect may be due to variability of data values at a separation distance smaller than the minimum distance between data locations, and/or the presence of measurement errors.

The variogram may reveal some degree of anisotropy in the spatial correlation among data; i.e. the variogram (or covariance) depends not only on the length of the separation vector, but also on its direction. Thus the variogram parameters for different directions are different from each other. The spatial correlation along the direction of sedimentation of a high permeability channel, for example, will be greater than the spatial correlation in the transverse direction. The type of anisotropy most commonly considered is geometric, where the sill is constant but the range varies with direction. The anisotropy is statistical, and does not refer to the local nature of the random variable, e.g. the local hydraulic conductivity. The random variable may still be a scalar, and this is how it is treated in this study. The variogram is fitted by using the exponential model. The hydraulic conductivity can be obtained for the entire domain of the true model.

Indicator Kriging

In this method, the distribution of hydraulic conductivities beyond the detection limit is also considered in addition to the scattering and spatial correlation. This is expected to be the most accurate method among the three methods. As in simple kriging, the properties of variance and spatial correlation were calculated from the artificial data. The spatial distribution of very low hydraulic conductivities has considerable impact on the movement of tracers, which tends to migrate around such areas. It is preferable to extract and use all possible information from the data. There are several ways to treat values which are below the detection limit. One such method is the application of indicator simulation, which uses all the data including the values below the detection limit. In the indicator approach, the data at each location x are transformed into a binary variable (x, z_c) consisting of only 1's and 0's, depending on whether the data value is below or above the indicator (cutoff) value z_c. This method has the important property that local hard indicator data originating from both local hard data and ancillary information that provides hard inequality constraints can be analyzed jointly (Journel and Alabert, 1990).

The first step of indicator simulation is the calculation of indicator variograms for a choice of cutoff values. The choice of the number of cutoffs is a balance between computational demand and a proper definition of the cumulative distribution function.

Figure 2 shows hydraulic conductivity values at sample locations for a heterogeneous model, and Figure 3 shows the locations of the predicted values of hydraulic conductivity for this model. The indicator for hydraulic conductivities in Figure 3 is shown in Table 1.

RESULTS AND DISCUSSION

Figure 4 shows the profiles of the distribution of contaminant concentration after various numbers of days using the classical model. The concentration fronts move steadily through the medium in conformity with the expected contamination migration pattern for the given soil characteristic. Figure 5 shows the contaminant concentration profiles for the stochastic model.

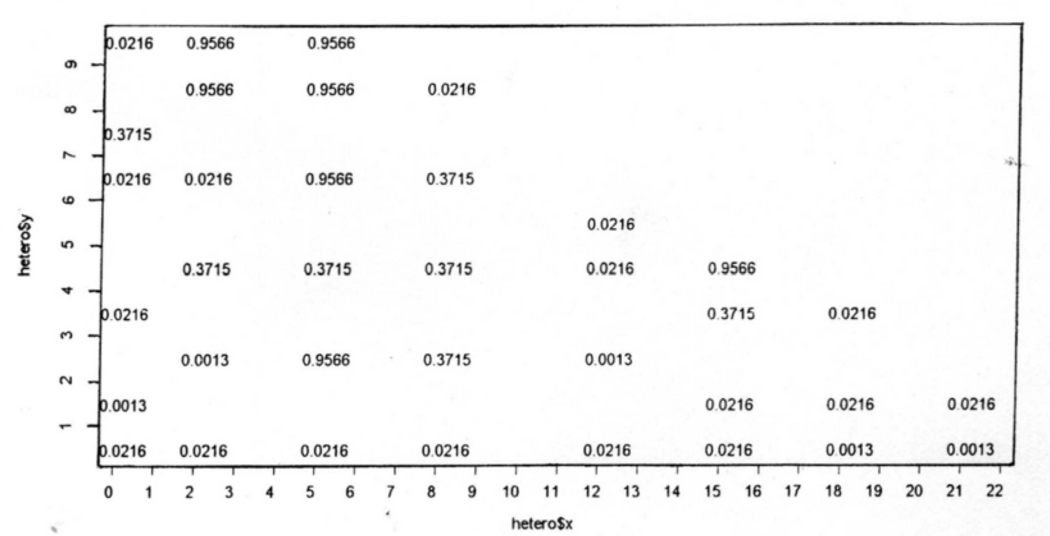

Figure 2. Hydraulic conductivity at sample locations for the stochastic model.

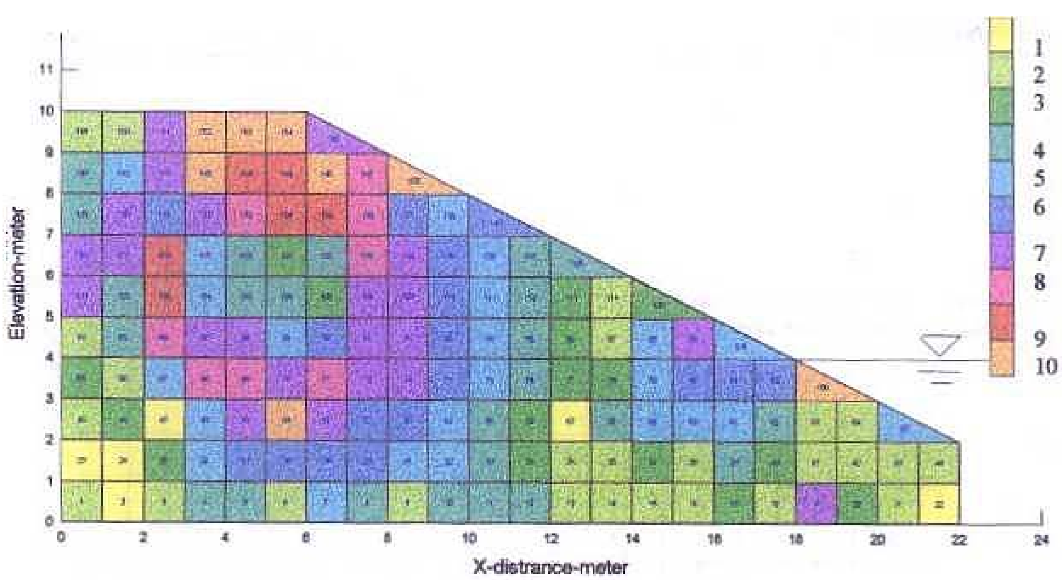

Figure 3. Arrangement of soil for the stochastic model.

Table 1. Generated hydraulic conductivity spread to 10 values

Type	1	2	3	4	5	6	7	8	9	10
Mean conductivity values, m/day	0.005	0.025	0.055	0.110	0.225	0.375	0.525	0.675	0.825	0.95

After short periods of less than seven days the concentration profiles were similar to those obtained using the classical model. However, for longer periods, the stochastic model produced more dispersed concentration fronts. This migration pattern reflects the influence of varied hydraulic conductivities resulting from the use of kriging techniques prior to the simulation of contaminant migration.

From the artificial hydraulic conductivity values, the necessary variogram of spatial distribution of hydraulic conductivities was generated. For short periods, the stochastic continuum model showed results similar to the classical approach. However, for longer periods the stochastic approach showed more dispersed concentration fronts. In actual practice about one third of field measurements were assumed to yield values below the detection limit of the measuring device. In order to preserve the full variability of the hydraulic conductivity and to account for its uncertainty at unsampled locations, multiple and equally likely stochastic realizations of its spatial distribution could be generated. A number of different stochastic realizations of hydraulic conductivity could be generated for input into available numerical flow and transport programs. Site investigations should also be conducted to obtain the field data for hydraulic conductivity.

Protection of the geo-environment could be made more secure through more accurate monitoring and control of potential contaminant migration to the groundwater system. Tools are available which make contaminant flow simulation more realistic and meaningful. Geophysical methods could also be used to improve the modeling and subsequent prediction of contamination problems. The seismic refraction method could be used to identify the potential reservoir that could be contaminated and the resistivity method could be employed in monitoring the actual contamination taking place.

As was mentioned earlier, the main objective of this paper was to show that the kriging technique was suitable in simulating contamination migration in a medium where the hydraulic conductivities are known at limited locations. The simulation results show that the kriging technique can be a useful tool in the prediction of contamination migration for a medium with varied or nonuniform hydraulic conductivities. The patterns of contamination migration obtained from the simulations were reasonable and confirmed expected contamination migration behavior.

CONCLUSION

The stochastic continuum model successfully generated the necessary variogram and a spatial distribution of hydraulic conductivities was generated. In actual practice, about one third of field measurements are assumed to yield values below the detection limit of the measuring device. To preserve the full variability of the hydraulic conductivity and to account for its uncertainty at unsampled locations, multiple and equally likely stochastic realizations of its spatial distribution can be generated. A number of different stochastic realizations of hydraulic conductivity can be generated for input into available numerical flow and transport programs.

Site investigation programs normally yield limited field data for hydraulic conductivity parameters. The technique proposed in this paper can be used in the modeling and subsequent

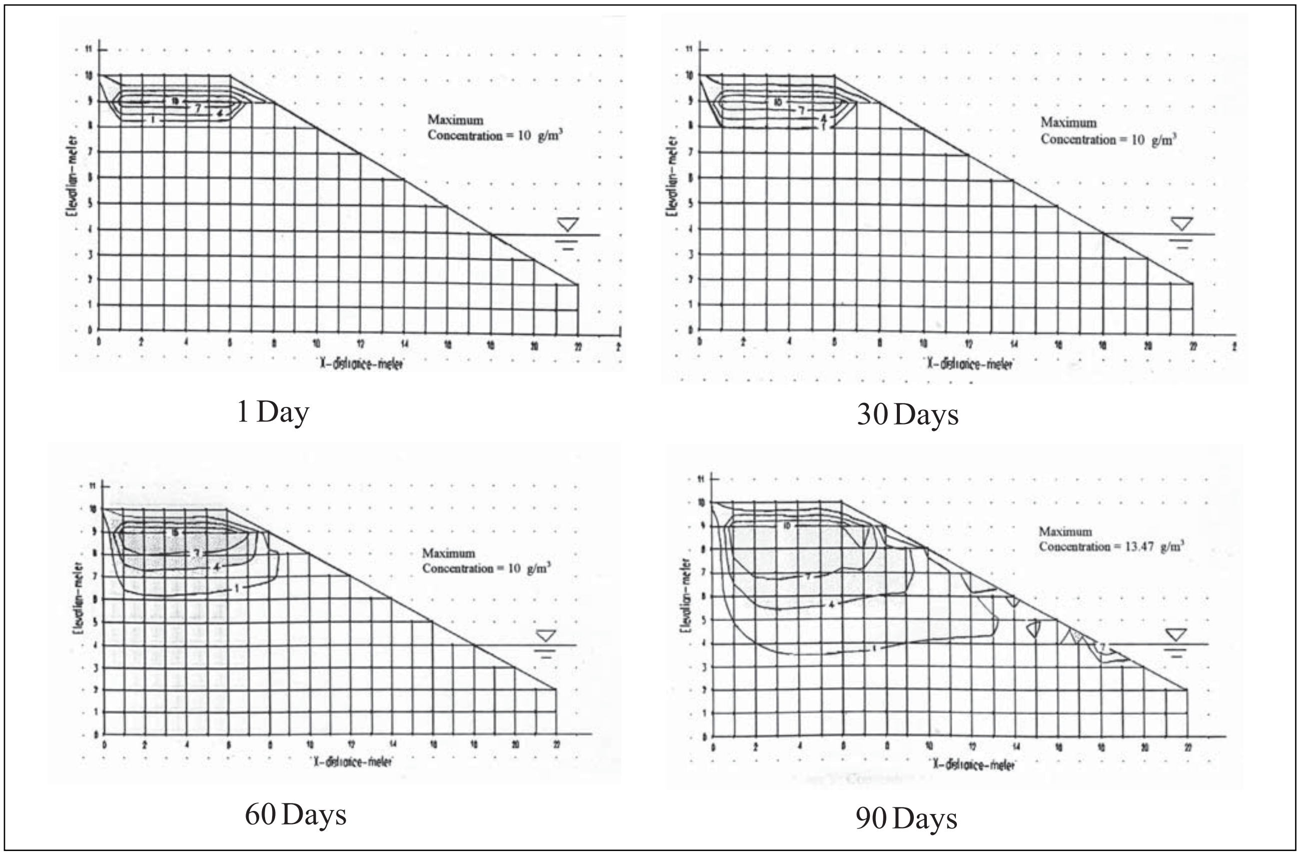

Figure 4. Classic model - concentration of contaminant contour values at 1, 30, 60 and 90 days.

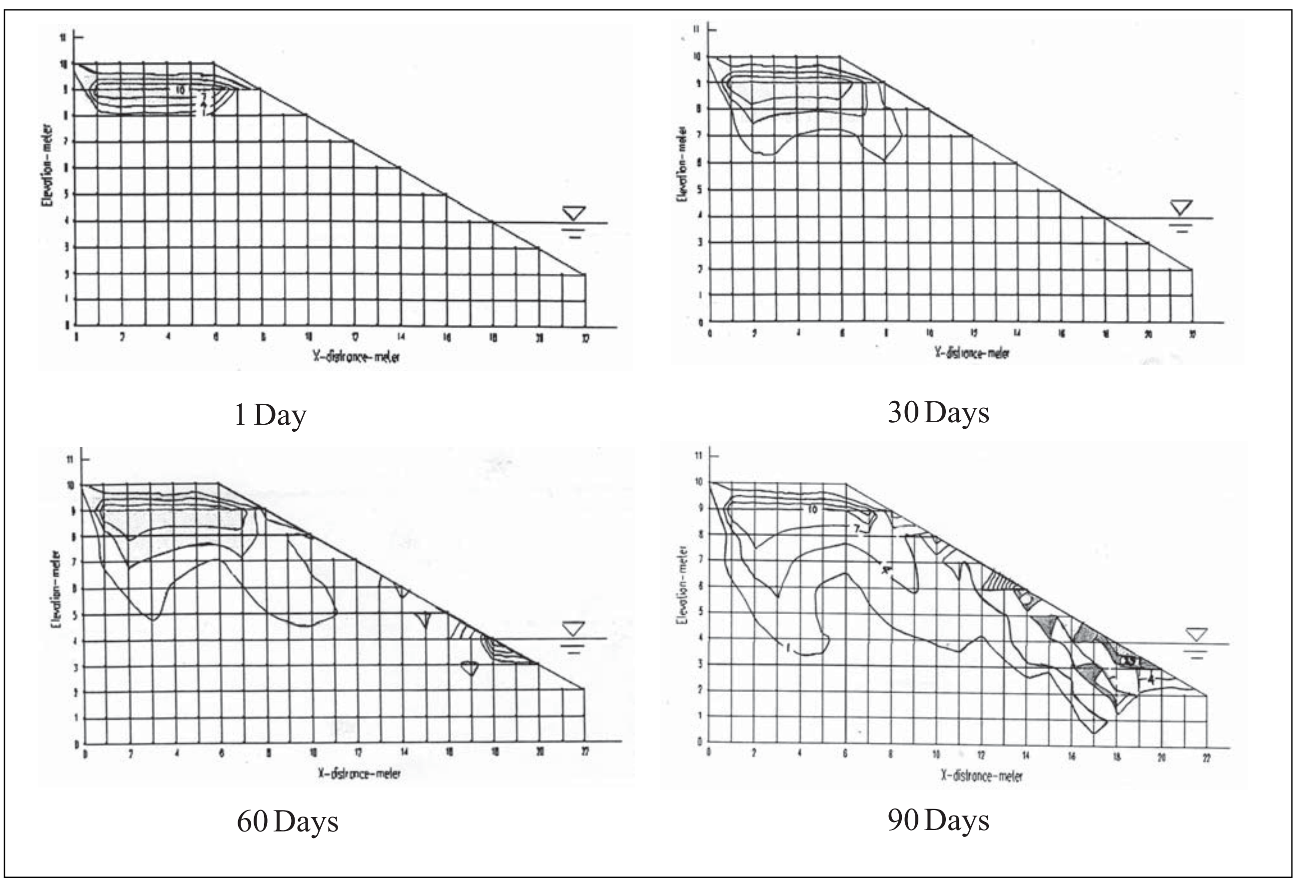

Figure 5. Stochastic model - concentration of contaminant contour values at 1, 30, 60 and 90 days.

prediction of contamination problems. Improved protection of the geo-environment can then be achieved through more realistic contaminant monitoring and better control of potential contamination of the groundwater system.

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