EVALUATING THE ENVIRONMENTAL CONSEQUENCES OF GROUNDWATER CONTAMINATION

I. An Overview of Contaminant Arrival Distributions as General Evaluation Requirements

by

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ABSTRACT

The environmental consequences of subsurface contamination problems can be completely and effectively evaluated by fulfilling the following five requirements:

1. Determine each present or future outflow boundary of contaminated groundwater
2. Provide the location/arrival-time distributions
3. Provide the location/outflow-quantity distributions
4. Provide these distributions for each individual chemical or biological constituent of environmental importance
5. Use the arrival distributions to determine the quantity and concentration of each contaminant that will interface with the environment as time passes.

The arrival distributions on which these requirements are based provide a reference point for communication among scientists and public decision-makers by enabling complicated scientific analyses to be presented as simple summary relationships.

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INTRODUCTION

The requirement for environmental impact analyses and statements evidences the growing public concern for environmental quality. These statements document the probable effect of a proposed or continuing action by man on the environment. They are intended to help public and regulatory authorities weigh and select the best options for using the environment to man's benefit, while guarding against any abuse of this privilege. Failure to adequately consider consequences or to clearly convey environmental effects in an understandable fashion can seriously impair the value of impact statements for decision-making purposes. If this occurs, the environmental statement concept degenerates to a costly bureaucratic ritual unable to accomplish the benefits intended.

Such pitfalls can be avoided by providing and complying with sound requirements for providing environmental evaluations. This paper recommends such requirements for evaluating groundwater contamination problems. Such requirements form the basis for two new distributions that effectively and simply summarize many complex hydrologic effects and can be used by decision-makers to predict possible environmental consequences.

In this paper, the results needed to evaluate the consequences of any subsurface contamination problem are first considered qualitatively. As these results are quantified, the two unifying distributions are obtained. These two simple distributions and their use to evaluate environmental consequences are then explained with the aid of a simple example. Finally, five requirements incorporating the new distributions are proposed as the basis for making administrative, judicial and public decisions on the control and assurance of groundwater quality.[2]

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[2] The emphasis in this paper is restricted to introducing and showing the usefulness of the contaminant location/arrival-time and outflow-quantity distributions

QUALITATIVE STATEMENT OF RESULTS NEEDED

What must be known to evaluate a groundwater contamination problem? In simple terms, the same three factors that are needed to evaluate present and future consequences of any environmental problem:

1. Location of contaminants
2. Arrival time of contaminants
3. Quantity of contaminants

These apply equally to feedlot seepage problems in agriculture, mine seepage losses in the mineral industries or disposal of industrial wastes (Kussmaul, 1971; Walker, 1969; Hacket, 1965). As various special problems from the many different applications are considered in more general terms, differences either disappear or are identified within these three basic items.

First, the location of the contaminant is important. A contaminant isolated from man--both now and in the future--may represent little hazard, even when large quantities are present. Under other conditions, small amounts of contaminants arriving at critical locations over a short period may involve severe hazard. The problem of the location is simplified by concentrating on those places where the subsurface contaminants will interface with the biosphere. Porous earth or rock material isolates the contaminant from the environment except at relatively few places of outflow from the subsurface system (e.g., springs, seepage into streams, rivers, swamps, lakes, oceans), or at places of man-made withdrawals from wells, drains, cisterns and mine shafts. Where the groundwater level is high, withdrawals by trees and other plants also can be an outflow boundary. All of these possible interfaces with the environment are categorized as contaminant outflow boundaries.

The time a contaminant will reach a critical location is another vital factor. If arrival is imminent, corrective actions are required immediately. However, longer travel times are usually involved in groundwater contaminant movement so less immediate action may be of greater benefit and result in considerable savings. Travel time periods of 1 to 10 years are common, and periods of 25 to 50 years or more are not at all unusual. For longer periods, much greater importance is placed on accurately predicting future conditions and knowing when the contaminants will arrive at a particular environmental interface.

Finally, of the three items, the quantity of the contaminant is the most important. Small amounts of contaminants may be little more than a nuisance while larger quantities usually constitute serious hazards; consequently, the amount and concentration must be identified to evaluate the environmental consequences of any problem.

Thus, three interrelated factors, (1) the location of the contaminant arrival on the outflow boundary, (2) the arrival time of contaminant at the boundary, and (3) the quantity of contaminant reaching the boundary, provide a concise statement of the information needed to evaluate the environmental consequences of subsurface contamination. The next objective is to interrelate these three factors to provide tools for the evaluation. This can be done utilizing two quantitative relationships or distributions: the location/arrival-time distribution, which interrelates factors 1 and 2; and the location/outflow-quantity distribution, which interrelates factors 1 and 3.

THE LOCATION/ARRIVAL-TIME DISTRIBUTION

The location/arrival-time distribution gives the location where the contaminant will reach the outflow boundary as a function of time. It provides the location of contaminant outflow as a function of time of the instantaneous pulse of traced fluid which departs from the contaminant source at time t_0. Three items are particularly important in this definition.

1. The location/arrival-time distribution gives the outflow location as the overall system response to all the factors affecting the flow paths and interim delays in the subsurface system.
2. Each and every arrival curve is the response of a specific infinitesimal volume leaving the contaminant source.

3. For each successive infinitesimal volume of fluid leaving the source there is a specific departure time t_0; hence for each t_0 there is an associated location/arrival-time curve.

Examination of a sample flow system will help illustrate this important distribution.

SAMPLE FLOW SYSTEM

As an example, we have selected an evaluation for leakage from a 600-foot pond located 1.85 miles from a river. There are presently no domestic wells between the pond and the river, nor will wells be drilled for domestic use in the future. Therefore, the only potential interface with human beings of any contaminants lost from the pond will be at locations where contaminated groundwater reaches the river.

Figure 1 shows the predicted worst-case consequences of the pond leakage. The shape and location of the contaminated front illustrated depicts the gradual movement from the pond toward the river 9,800 feet

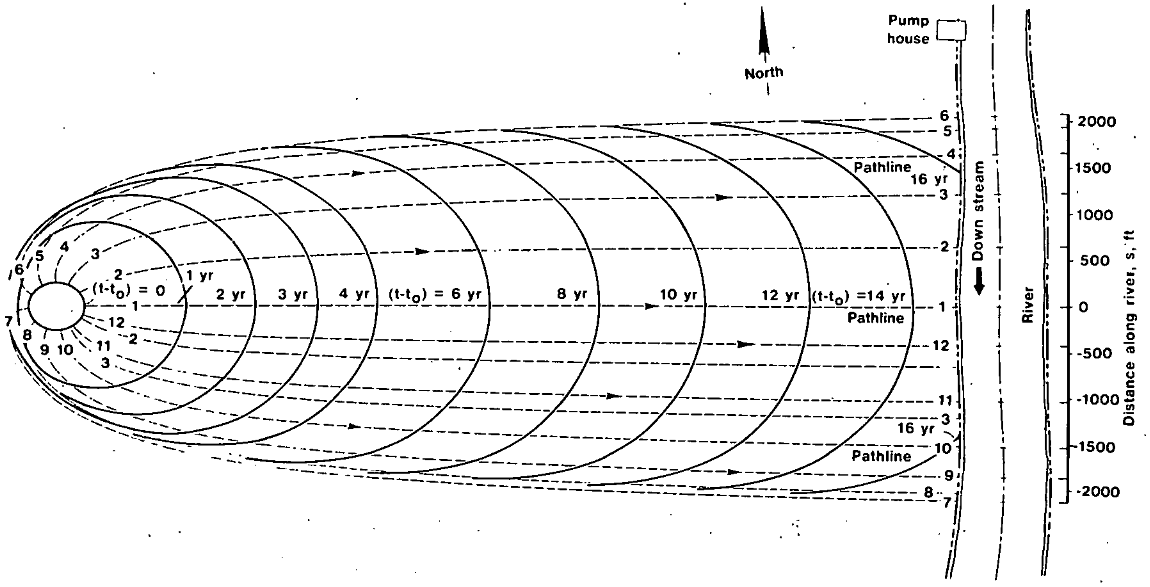

Figure 1. The gradual movement of contaminated groundwater from the pond toward the river

away. Beginning at the pond's edge, the contaminated front slowly moves outward in ever-elongating arcs toward the river as indicated. Contaminants seeping along the shortest paths first reach the river some 14-plus years after the initial contaminant outflow.

The dashed curves in Figure 1 represent some of the flow paths of contaminated fluid. The first contaminated fluid to reach the river moves along the shortest straight pathline, number 1, directly to the river and arrives in slightly less than 14.9 years. For the fluid moving in the longer curved flow paths, more time is required. For example, along pathlines 4 and 9 it takes 16.5 and 17.2 years, respectively, for the contaminated fluid to reach the river. For longer pathlines, such as 6 and 7 in the figure, the elapsed travel times are 19.3 and 21.8 years, respectively. Although not all pathlines are shown in Figure 1, a complete spectrum of pathlines covers the entire range of travel times between the 14.9 and 21.9 years. Additional data for the pathlines are summarized in Table 1 for use in obtaining the location/arrival-time and the location/outflow-quantity distributions.

The location/arrival-time distribution shows where the contaminated flow emerges at the outflow boundary as a function of time. This location is given as the distance from a specific reference point or as coordinates on the outflow surface. For example, in the flow system shown in Figure 1, the location along the river where contaminants will emerge with passing time needs to be determined. In this case, it is convenient to designate the locations along the river in terms of positive distances (+s) upstream and minus distances (-s) downstream from the point where the center pathline 1 enters the river. Using the distances along the river and arrival times, the location/arrival-time curve for the sample flow system is plotted as in Figure 2. In this figure, the location ±s along the river where the contaminated fluid enters is plotted against the successive times of arrival from Table 1.

In Figure 2, the contaminated fluid location/arrival-time curve is a smooth and regular distribution--a result of the simple steady flow

Table 1. Data for the contaminant location/arrival-time and outflow-quantity distributions for the sample flow system

[1] Pathline designation	[2] Fluid travel time along pathline, $T-t_o$, yr	[3] Location along river bank from center of flow, ±s, ft	[4] Outflow rate, q, gal/min/ft	[5] Strontium** ion arrival time at river bank, T_s-t_o, yr
1	14.88	± 0.0	0.111389	171.12
--	14.90	± 140.0	0.111387	171.35
12, 12'*	14.96	± 426.3	0.111374	172.04
2, 2'	15.07	± 650.5	0.111354	173.31
--	15.10	± 700.0	0.111348	173.65
--	15.20	± 856.0	0.111329	174.80
--	15.30	± 960.0	0.111313	175.95
11, 11'	15.41	±1032.5	0.111302	177.22
--	15.50	±1128.0	0.111285	178.25
3, 3'	15.65	±1219.8	0.111267	179.98
--	15.80	±1330.0	0.111245	181.70
--	16.00	±1433.0	0.111222	184.00
10, 10'	16.19	±1516.0	0.111203	186.19
4, 4'	16.52	±1649.7	0.111170	189.98
--	16.75	±1720.0	0.111151	192.63
--	17.00	±1790.0	0.111132	195.50
9, 9'	17.21	±1842.7	0.111117	197.92
5, 5'	17.64	±1921.2	0.111095	202.86
--	18.00	±1972.0	0.111080	207.00
8, 8'	18.57	±2023.0	0.111064	213.56
--	19.00	±2048.0	0.111056	218.50
6, 6'	19.26	±2060.4	0.111052	221.49
--	19.50	±2070.0	0.111049	224.25
--	20.00	±2079.0	0.111047	230.00
--	20.50	±2088.0	0.111044	235.75
--	21.00	±2096.0	0.111041	241.50
--	21.50	±2103.0	0.111039	247.25
7, 7'	21.84	±2109.0	0.111038	251.16

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*Pathlines with no designation and those with a prime (e.g., 12' or 2') are not shown in Figure 1.

**The basis of the strontium arrival times is described in the "Contaminant Concentration and Outflow Rates" section.

system involved. Papers II, III and IV will give better insight into the irregular tendencies of location/arrival-time distributions.

USE OF THE LOCATION/ARRIVAL-TIME DISTRIBUTION

The location/arrival-time distribution can be easily used to determine the expected location of any outflow that may interface with human beings. To illustrate, consider a worst-case release of 210 million gallons requiring 0.85 years, or slightly more than 310 days, to leak from the pond.

The arrival curves for a contaminant-release time of 310 days or 0.85 years are shown in Figure 3. The arrival location curves for $t_0 = 0$ years and for the last of the 210 million gallons of contaminant released at $t_0 = 0.85$ years are shown. All locations of contaminated fluid arrival at the outflow boundary lie between the $t_0 = 0$ and

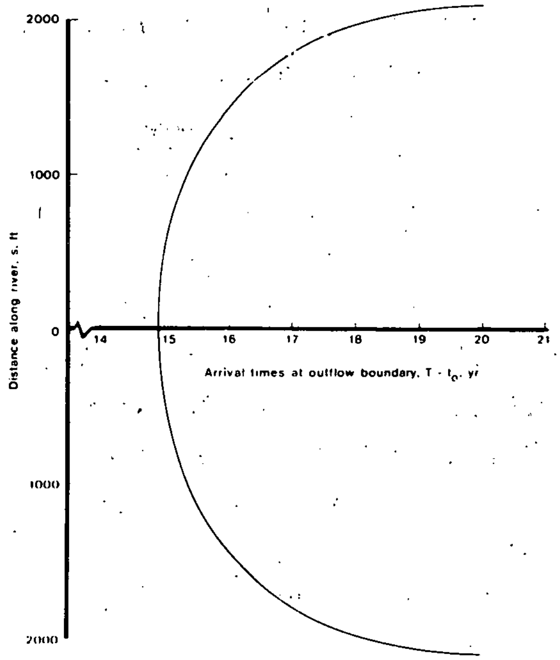

Figure 2. The location/arrival-time distribution for contaminated groundwater entering river

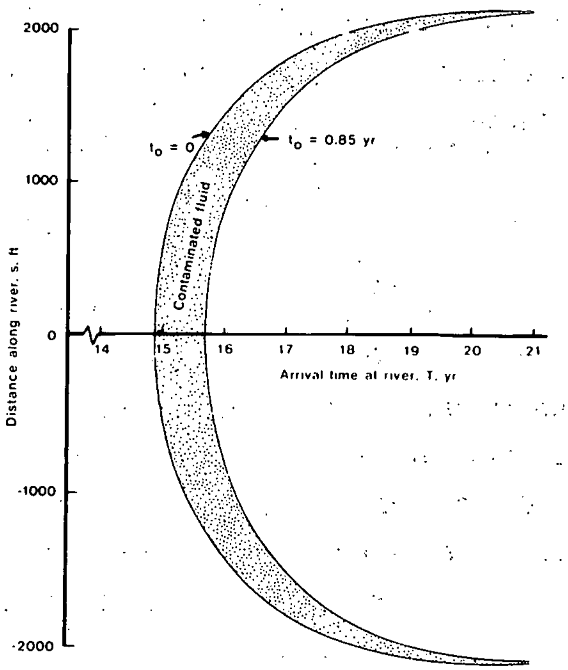

Figure 3. Use of location/arrival-time distributions to determine the location of contaminant outflow along river

t_o = 0.85 curves. Therefore, at any time T, all those locations of contaminant outflow from the subsurface into the river lie between the two curves. For example, at T = 16 years contaminated water will only flow into the river between s = +800 and +1433 feet as well as between s = -800 and - 1433 feet. At T = 17 years the outflow into the river occurs between s = +1500 and +1790 feet, and also between s = -1500 and -1790 feet. The greatest inflow of contaminated fluid would appear to occur at T = 15.73 years. At this time, from Figure 3, the river inflow is occurring at all locations between s = -1260 feet and s = +1260 feet. Later at T = 18 years less inflow would appear since the river entry is only between s = 1820 and 1972 feet upstream and downstream between -1820 and -1972 feet. In effect, the results in Figure 3 completely provide locations of potential interface between the environment and the subsurface contamination.

Whereas the location/arrival-time distribution relates the arrival location of contaminant along the outflow boundary to the arrival time of the contaminant at this boundary, the second important distribution relates the location along the outflow boundary to the quantity of contaminant outflow.

THE LOCATION/OUTFLOW-QUANTITY DISTRIBUTION

The location/outflow-quantity distribution gives the amount of outflow at various locations along the environmental interface. More specifically, it is the variation of the outflow rate or flux as a function of the location where the contaminated fluid or contaminant exudes on the outflow boundary at a particular time T. Three items are particularly important in this definition:

1. The particular location on the outflow boundary where outflow occurs is specified.
2. The outflow rate or flux at each location is specified.
3. The time dependence of outflow as a function of location is specified by successive arrival curves.

Accordingly, there is generally a separate and distinct location/outflow-quantity distribution for each and every arrival time at the outflow boundary. With the location/outflow-quantity distributions available, the quantities that may interface with the environment are readily obtained. The same sample flow system used earlier can also illustrate this distribution.

SAMPLE FLOW SYSTEM

In the example, location/outflow-quantity distributions provide the rate or flux along the outflow boundary (i.e., the river). In particular, the values of outflow flux q from Column 4 in Table 1 are plotted against the locations along the riverbank s from Column 3 to provide the location/outflow-quantity distribution shown in Figure 4. The location/outflow-quantity curve is easily used with the location/arrival-time curves in Figure 3 to determine the overall contaminated fluid outflow to the river.

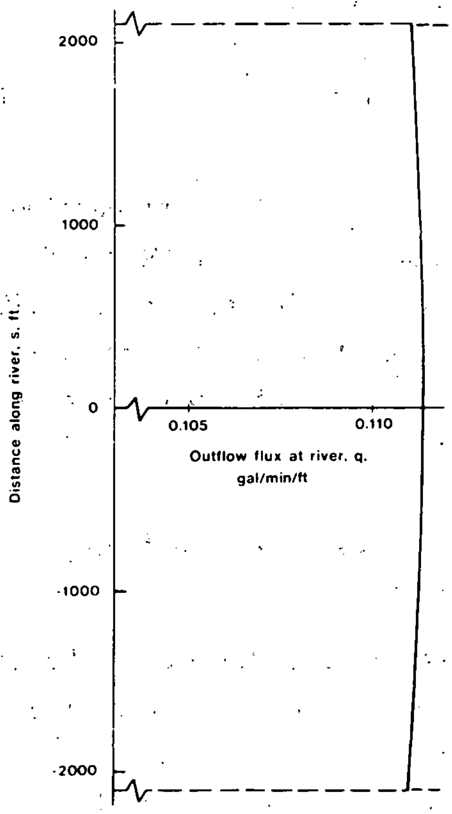

Figure 4. The location/outflow-quantity distribution along river

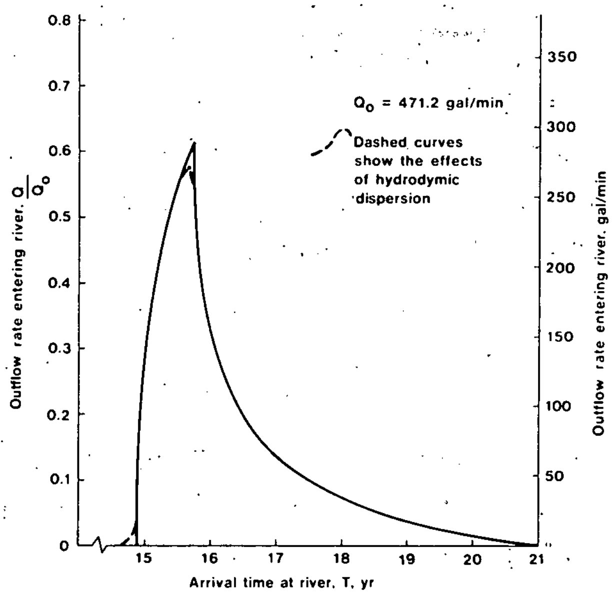

Figure 5. The contaminated fluid outflow rate entering river as a function of time

The rather uniform outflow rates apparent in Figure 4 are a natural consequence of the simple flow system involved. Also, the example has only steady flow so there is only one location/outflow-quantity curve, rather than several curves as would occur if the groundwater system involved transient flow.

USE OF THE LOCATION/OUTFLOW-QUANTITY DISTRIBUTION

To illustrate use of the arrival results, again consider the leakage case discussed earlier, involving 210 million gallons over a 0.85 year period. From Figure 3 the locations where contaminants are outflowing at a given time are easily obtained; i.e., at T = 15.35 years all of the outflow between s = -1000 feet and s = +1000 feet is contaminated fluid entering the river. If the varying outflow rate q in Figure 4 is integrated between the limits of s = -1000 and s = +1000 feet, then the total contaminated water outflow rate Q_T into the river would be obtained at the time T = 15.35 years, i.e.:

$$Q_{T = 15.35\ \mathrm{yr}} = \int_{-1000\ \mathrm{ft}}^{1000\ \mathrm{ft}} q\, ds = 228.06\ \mathrm{gal/min} \tag{1}$$

At a later time of T = 17 years from Figure 3 the contaminant outflow is in two sections with one outflow section between s = -1790 feet and s = -1500 feet and the other section between s = 1500 feet and s = 1790 feet. Again, integration between the limits on the location/outflow-quantity distribution gives the contaminated water outflow rate to the river at T = 17 years:

$$Q_{T = 17\ \mathrm{yr}} = \int_{-1790\ \mathrm{ft}}^{-1500\ \mathrm{ft}} q\, ds + \int_{1500\ \mathrm{ft}}^{1790\ \mathrm{ft}} q\, ds = 64.55\ \mathrm{gal/min} \tag{2}$$

Graphically, the integrations in Eq. (1) and (2) are represented by the areas to the left of the s vs q curve in Figure 4 and bounded by the appropriate s locations along the river bank as obtained from the location/arrival-time distribution in Figure 3. At any other time T, by integrating the q as shown in Figure 4 between the appropriate limits obtained from Figure 3, the quantity of contaminated water entering the river is obtained.

The results of using the location/arrival-time curve in Figure 4 and the location/outflow quantity curve in Figure 3 provide the required outflow rate of contaminated fluid entering the river as shown in Figure 5. The left-hand ordinate is the ratio of the outflow rate Q to the steady pond discharge Q_0; hence Figure 5 gives the fractional contaminated fluid outflow rate. The right-hand scale provides the actual outflow rate in gallons per minute as a function of time. The contaminated fluid outflow begins slowly at 14.88 years, soon rises to a peak of 289.8 gallons per minute, and then recedes, at first rapidly and finally diminishing gradually to no contaminant outflow. The small effect of true hydrodynamic dispersion as contrasted to megascopic dispersion (Schwartz, 1976) is also indicated in Figure 5 by the dashed curves. Its effect was incorporated here using the methods of Nelson and Reisenauer, 1963. In general, true dispersion has only a very slight smoothing effect, so it is not further considered here.

The curve in Figure 5 represents the amount of contaminated water entering the river as a function of time, which is the crucial result needed to evaluate the environmental consequences. Two characteristics of this peaking curve should be noted. First, the peak value is obviously important as the maximum outflow rate. Second, the low continuing tail of the curve, which persists for a longer time, is important because the cumulative effects of many such continuing tails from different sources on a single river can be a major problem. In analysis, the flow into the river as a function of time is seen to be rather small, with the maximum or peak value of less than 289.8 gallons per minute occurring 15.73 years after the first contaminated leakage began from the reservoir. However, the effect of the smaller tail of the curve must be considered along with entry rates of other contaminant sources along the river.

Thus far, the evaluation has been limited to the contaminated water arrival. It is also important to consider the chemical concentrations and amounts of the various contaminants expected to arrive at the river.

CONTAMINANT CONCENTRATION AND OUTFLOW RATES

The concentration and outflow rates of the particular contaminant arriving at the river depend on the original concentration, the groundwater flow rate, and whether or not that particular contaminant moves directly with the water or is sorbed by porous material (Nelson, 1963 and 1965). If the contaminant moves directly with water (is essentially fluid coincident), then the water arrival curves are also the concentration outflow arrival distributions and only minor further evaluation is necessary (Nelson, 1966). For example, in determining quantities and concentrations of sulfate entering the river, geochemical reactions are usually of minor importance and the sulfate is considered to move with the water. By simply using the original concentration at the reservoir times the q values in Table 1, the sulfate location/outflow distribution at the river (similar to Figure 4) is obtained. This distribution could be used with Figure 3 as described to obtain a low-peaking curve for the expected sulfate outflow to the river as a function of time. Other water coincident constituents such as chlorides and nitrates may be similarly considered.

Further evaluation is required for contaminants that interact with the porous material by geochemical reactions. More complicated geochemical systems of this type involve a complete transport analysis similar to that described by Schwartz and Domenico (1973) in order to obtain location/chemical-outflow quantity and arrival-time distributions for each individual chemical component. In some simpler situations involving trace concentrations of the chemical constituents and equilibrium chemical reactions, approximate time lag evaluations are both adequate and useful (Kaufman, 1959). Such an evaluation makes it possible to estimate the exchange effects on the movement of a contaminant such as strontium. Kaufman's approach was used to calculate the time lag. From the time lag the arrival times for strontium were calculated (see Column 5 of Table 1).

It is convenient to illustrate the chemical arrival distributions using strontium as an example. There is no radioactivity involved, so decay need not be considered. The strontium outflow location/arrival-time distribution is shown in Figure 6 and is a plot of the results in Columns 3 and 5 of Table 1. The resulting curve is very similar to Figure 2 except the curve provides the arrival time of a single chemical constituent, in this case strontium, at various locations along the river outflow boundary. The strontium location/arrival-time curve can be used as previously described to obtain the contaminant inflow rate to the river, provided the second arrival distribution is also obtained.

The second distribution, the arrival location/outflow-quantity distribution for strontium, is obtained using the reservoir concentration of strontium (C_{Sr}), the fluid outflow flux q and the arrival locations along the river. To illustrate, suppose the concentration of strontium seeping from the reservoir for an elapsed time of 0.85 years were 1.67×10^{-7} pounds per gallon. Since the approximate time lag method is being used and hydrodynamic dispersion is neglected, the outflow rate of strontium is obtained as the concentration of strontium per gallon times the fluid flux q from Table 1. Accordingly, after converting units, the strontium outflow rate q_{Sr} in pounds per year is:

$$q_{Sr} \text{ (in lb/yr)} = 8.754\ q \qquad (3)$$

where q is in gallons per minute as in Column 4 of Table 1. The complete strontium arrival location/outflow curve is plotted in Figure 7 and is similar to the contaminated fluid results in Figure 4. The variation of contaminant (strontium) outflow to the river with time is obtained as before by integrating the outflow (Figure 7) between the appropriate limiting outflow locations from Figure 6 or from Table 1. Repeated evaluations using the two arrival distributions provide the complete outflow rate of strontium to the river shown in Figure 8.

In retrospect, the results in Figures 6 and 7 completely interrelate the quantity, arrival time and the location of potential contaminant interface with the environment. From these two basic curves comes the final result in Figure 8, which permits direct evaluation of the environmental consequences.

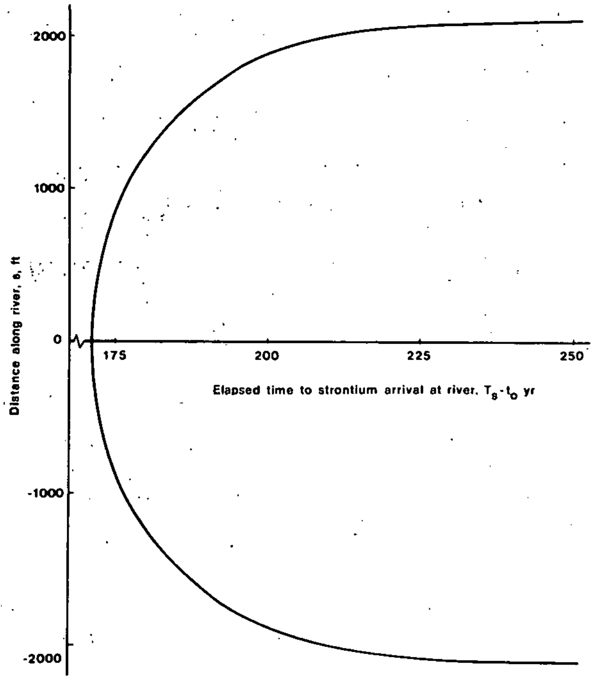

Figure 6. The outflow location/arrival-time distribution for strontium entering the river

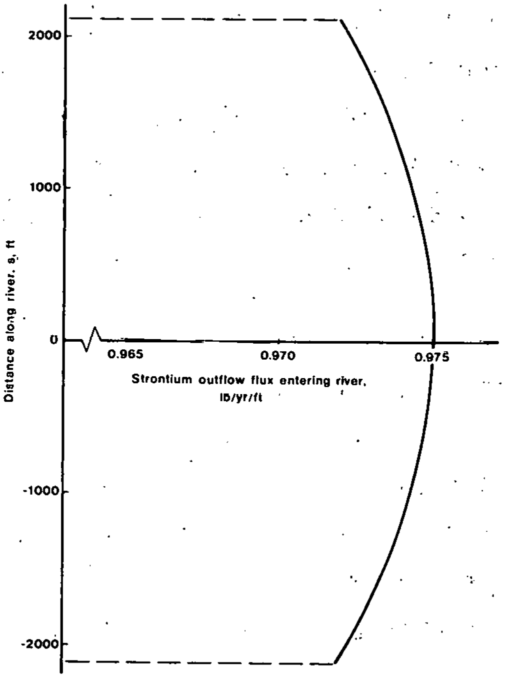

Figure 7. The strontium location/outflow flux entering the river

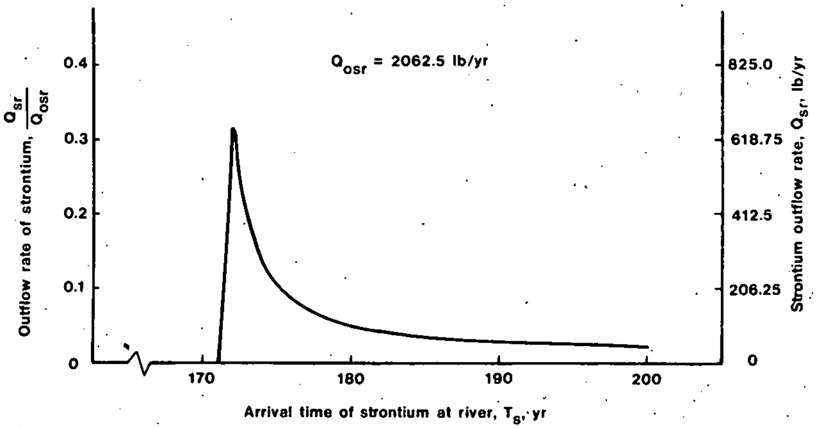

Figure 8. Strontium outflow rate entering the river

FIVE REQUIREMENTS FOR ENVIRONMENTAL EVALUATIONS

Results of the sample case demonstrated to this point show that evaluating the consequences of any subsurface contamination problem involves the careful determination of any present or future groundwater outflow boundaries of importance. At each boundary, the environmental determination is contingent upon: (1) the location of the contaminant arriving at that boundary, (2) the time of arrival of the contaminant at the boundary, and (3) the quantity of contaminant reaching the boundary. These items have been interrelated and incorporated into the two quantitative distributions described in the preceding sections. These distributions provide the key to satisfying the five following unified requirements, which in turn will yield results needed to quantitatively evaluate any subsurface contamination problem:

1. Determine each outflow boundary of contaminated groundwater that may now or in the future interface with the environment.
2. Provide the contaminated fluid location/arrival-time distribution for each outflow boundary in Item 1 (see example in Figure 2).
3. Provide the contaminated fluid location/outflow-quantity distribution for each outflow boundary in Item 1 (see example in Figure 4).
4. Provide the contaminant location/arrival-time and outflow-quantity distributions for each individual chemical or biological constituent of environmental importance in the contaminated fluid considered in Items 1, 2 and 3 (see example in Figures 6 and 7).
5. Determine the amount and concentration of each contaminant constituent that will, with passing time, interface with the environment. This is accomplished through use of the arrival distributions from Items 2, 3 and 4 (see example in Figure 8).

Satisfying these five requirements assures that the environmental consequences of any subsurface contamination problem can be evaluated. Therefore, these requirements, incorporating these simple distributions, are proposed as a sound technical basis for making decisions affecting the management of groundwater quality. Within this concise set of requirements lies the opportunity to harmoniously merge the efforts and facilitate the interchange of information between the decision-makers and the scientific disciplines providing the basic information.

For the decision-makers, the evaluation of environmental consequences is reduced to understanding two techniques that can be readily mastered; i.e., the location/arrival-time and location/outflow-quantity distributions. Mastering these distributions is far easier than facing the myriad of technical considerations involving permeability, porosity, hydraulic gradients, boundary types, isotropy, heterogeneities, dispersive effects and, in short, all of the geologic, hydrologic and analytical modeling considerations necessary to arrive at the location/arrival distributions. Perhaps the most important benefit to the decision-maker is the assurance that the tools to quantitatively determine present and future environmental consequences are at his disposal. Thus, he can make meaningful decisions based upon the information provided by the technical specialists.

The greatest value to the scientist or engineer is that these five concise requirements provide a specific means of setting goals and objectives and of communicating with political decision-makers and the public. Since decision-makers usually authorize, finance and accept environmental evaluations, it is essential that there be a viable communications link with them. Direct economies also result from the sharper focus on what is really needed to determine environmental consequences.

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