EVALUATING THE ENVIRONMENTAL CONSEQUENCES OF GROUNDWATER CONTAMINATION

IV. Obtaining and Utilizing Contaminant Arrival Distributions in Transient Flow Systems

by

R. William Nelson[1]
Staff Specialist, Scientific Systems Department
BCS Richland, Inc.
Richland, Washington 99352

ABSTRACT

The versatility of the new contaminant arrival distributions for determining environmental consequences of subsurface pollution problems is demonstrated through application to a transient flow system. Though some of the four phases of the hydrologic evaluations are more complicated because of the time-dependence of the flow and input contaminant concentrations, the arrival distributions still effectively summarize the data required to determine the environmental implications. These arrival distributions yield two graphs or tabular sets of data giving the consequences of the subsurface pollution problems in a simple and direct form. Accordingly, the public control authorities would be able to use these results to choose alternatives or initiate corrective actions, depending on the indicated environmental consequences.

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INTRODUCTION

The previous papers in this sequence presented the location/arrival-time and location/outflow-quantity distributions as simple, effective tools for evaluating subsurface pollution (Papers I, II, and III). The extensive geologic and hydrologic evaluations needed to obtain these arrival results were shown to include four phases--system identification, new potential determination, flow system kinematics, and contaminant transport analysis. System identification involves determining and measuring those physical and chemical characteristics pertinent to evaluating the subsurface contaminant movement. Determination of new potential variations involves all of the methods useful in finding the groundwater potential for future conditions. Building upon the results of these two phases to describe the geometry of fluid motion, the flow kinematics step provides the flow paths and the elapsed time for advancing fluid fronts. The last step, contaminant transport analysis, includes all of the additional formulations and evaluations necessary to incorporate the retarding effects of dispersion, sorption or other geochemical reactions between individual constituents and the porous material. Various phases of the evaluation have been emphasized through examples selected to illustrate specific aspects of the analysis for steady flow systems.

This paper elaborates on the technical basis of arrival distribution by describing use of these tools under transient flow situations in homogeneous material. The example used to illustrate these techniques, though restricted to two-dimensional flow, considers the environmental implications of contaminant movement under moderately complicated conditions where the flow regime is changing with time. First, the specific characteristics involved in considering the more generally encountered transient flow systems are illustrated. The hydrologic evaluation results are next utilized to satisfy the general requirements
Paper I) that assure a complete and sound evaluation of environmental consequences. Since these requirements involve the contaminant arrival distributions, the steps necessary to obtain the contaminant location/arrival-time and location/outflow-quantity distributions from the

hydrologic analysis are described for transient subsurface flow systems. Together, these arrival results are used to determine the environmental implications. The final results give the amount and concentration of contaminants, emerging with passing time, which will interface with man's environment.

OBTAINING ARRIVAL DISTRIBUTIONS FOR TRANSIENT FLOW SYSTEMS

Many of the same methods discussed for steady flow systems are used to obtain arrival distributions for transient flow systems; e.g., the detailed identification analyses for the various steady systems illustrated in the preceeding papers. The additional considerations involved with transient flow systems result from the new potential determination phase of the analysis. Such changes in potential with time also result in more complicated flow kinematics and transport analysis phases.

An example flow system is used to clarify the specific requirements for transient systems. This example, selected to illustrate the peculiarities of transient situations, is closely akin to the example used in Paper II. Therefore, the mathematical detail can be minimized here, yet all pertinent results are available in the previous paper. The four phases of the hydrologic evaluation are considered in the following topics.

SYSTEM IDENTIFICATION FOR TRANSIENT EXAMPLE

The two-dimensional example involves lateral flow in a homogeneous and isotropic porous slab of constant thickness and infinite lateral extent. The combined flow system includes a uniform lateral flow, altered by flow from a completely penetrating cylindrical pond and an injection well. The porous material is idealized to a homogeneous slab. The transient potential distribution is moderately simple, but the flow system kinematics illustrates a variety of the techniques required to find and use the arrival distributions. The specific flow system parameters for the example case are summarized in Figure 1.

NEW POTENTIAL DISTRIBUTION FOR EXAMPLE CASE

The potential distribution for the example flow system can be approximated satisfactorily by superposition of elementary flows. In particular, a uniform lateral flow of gradient strength U inducing flow in the positive x coordinate direction is added to a combined line source and positive doublet (Shames, 1962) centered at the origin to represent outflow from the completely penetrating cylindrical pond. The injection well is superimposed as a vertical line source, but with a small radius used to begin considering pathlines. Thus, an expression for the overall groundwater potential throughout the slab is provided.

Specifically, the potential ϕ is given by Eq. (1) in Paper II but with

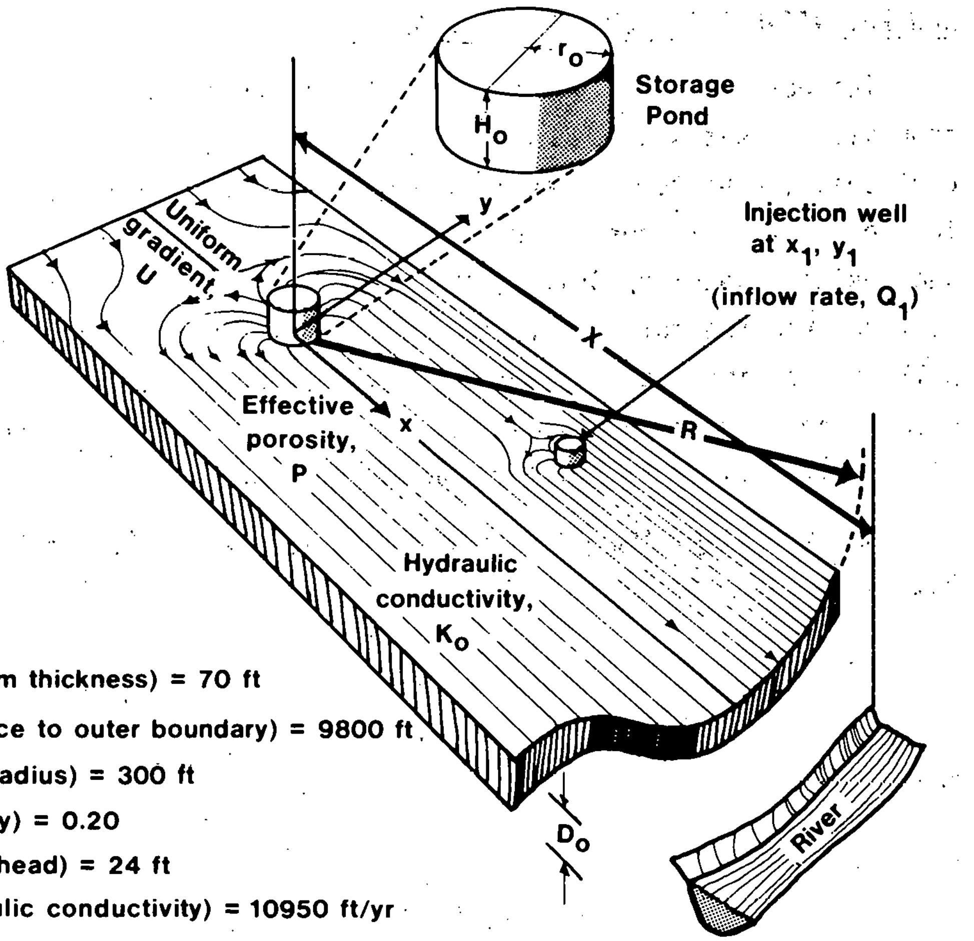
$$\begin{aligned} H' &= 1 \\ N &= 1 \\ j &= 1 \end{aligned} \tag{1}$$

and

$$Q_1 = Q_I + \frac{2\left(Q_M - Q_I\right)\frac{t}{t_n}}{\left(\frac{t}{t_n}\right)^2 + 1} \tag{2}$$

where Q_M, Q_I, and t_n are defined in Figure 1 and all the other terms are defined in Eq. (1) or as in Paper II. The injection rate in Eq. (2) introduces the time dependence into the system. In particular, the parameters in Figure 1, when used in Eq. (2), give an initial injection rate at $t = 0$ of 1.0×10^6 ft^3/yr. The injection inflow rate rises to 2.6×10^7 ft^3/yr at 1.5 years and then gradually diminishes toward the initial injection rate of 1.0×10^6 ft^3/yr.

The potential distribution throughout the flow system varies with time as the injection rate Q_1 changes in accordance with Eq. (2).



1. D_o (stratum thickness) = 70 ft
2. R (distance to outer boundary) = 9800 ft
3. r_o (pond radius) = 300 ft
4. P (porosity) = 0.20
5. H_o (pond head) = 24 ft
6. K_o (hydraulic conductivity) = 10950 ft/yr
7. U (uniform gradient) = 0.0095 ft/ft
8. X (distance to river) = 9800 ft
9. x_1 (x-coordinate of injection well) = 4000 ft
10. y_1 (y-coordinate of injection well) = 500 ft
11. Q_I (initial injection rate into well) = $+1.0(10^6)$ ft^3/yr
12. Q_M (maximum injection rate to well) = $+2.6(10^7)$ ft^3/yr
13. t_n (time parameter in Q, Eq. (2)) = 1.5 yr
14. C_o (scaling input concentration) = $8.33(10^{-4})$ lb/gal

Figure 1. Parameters for the example flow system

Specifically, the time-varying potential distribution is provided by use of Q_1 in Eq. (1) of Paper II. The resulting potential function is available for subsequent use in determining the flow system kinematics.

EXAMPLE FLOW SYSTEM KINEMATICS

The flow system kinematics provide the pattern, or geometry of flow, in the subsurface system. The paths of flow are needed for individual fluid particles moving through the flow system to the points of emergence at the outflow boundaries. These and the arrival time of fluids at outflow boundaries are determined by the pathlines. The characteristic differential equations for the pathlines are Eq. (3) and (4) in Paper II, appropriately using Eq. (1) and (2) from this paper to introduce the time dependence. Also, the initial conditions for the pathline differential equations are the starting coordinates for the contamination; i.e., either Eq. (5), (6) and (7) in Paper II or, for the injection well

$$x(t_o) = x_{0,1} \tag{3}$$

and

$$y\ (t_o) = y_{0,1} \tag{4}$$

with

$$\left(x_{0,1}\right)^2 + \left(y_{0,1}\right)^2 = \left(r_{0,1}\right)^2 \tag{5}$$

where $x_{0,1}$ and $y_{0,1}$ are the x and y coordinates around the injection well of radius $r_{0,1}$. This small circular radius is used as the surface for beginning the pathlines originating at the vertical line source.

The pathline differential equations subject to the above initial conditions were solved to yield the pathlines and travel times from the pond and injection well. These calculated results, using a fourth-order Runga Kutta solution scheme, are shown in Figures 2 and 3 with the detailed numerical results summarized in Table 1. Figures 2 (a, b, c) and 3 (a, b) show the pathlines and locations of fluid particles that departed from the pond and injection well at the times 0, 2, 4, 8 and

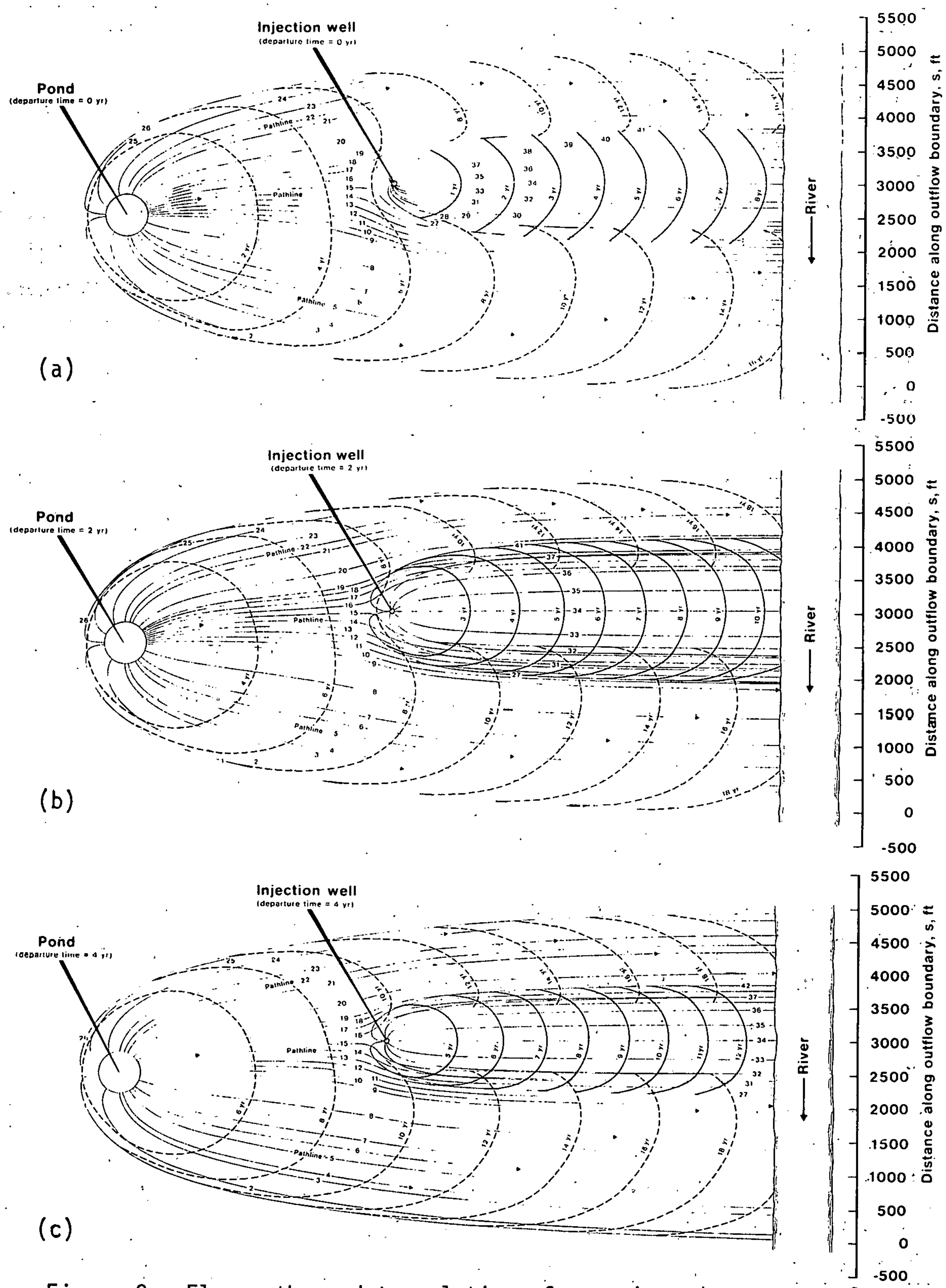


Figure 2. Flow paths and travel times for various departures of fluid in transient groundwater movement toward the river

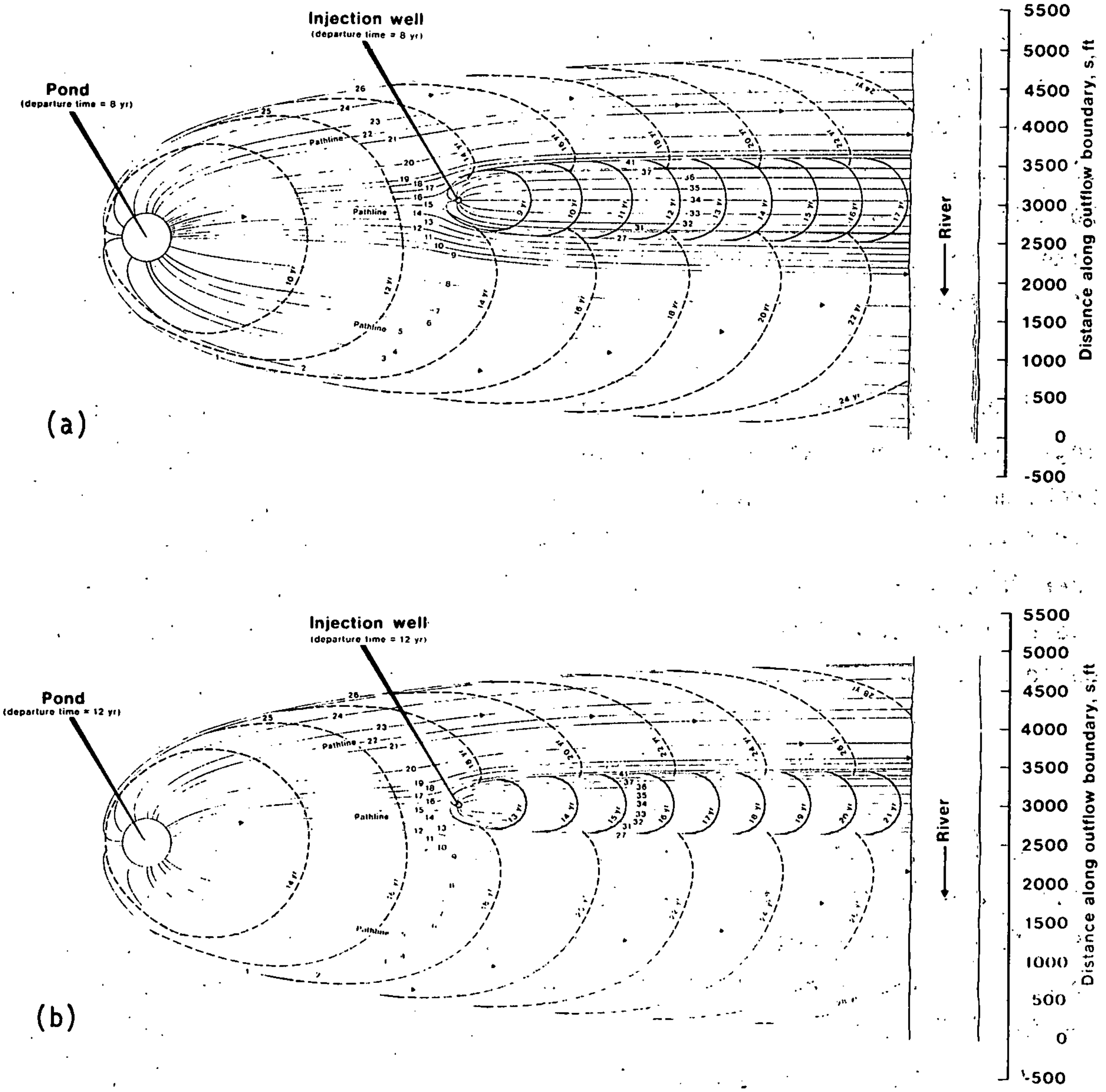


Figure 3. Flow paths and travel times for additional departure times of fluid in transient groundwater movement toward the river

12 years, respectively. The injected fluid body that is well developed in Figure 2(a) continues to expand in 2(b), but then gradually diminishes in significance in the flow patterns for the later departure times. The flow results in these figures and in the tabulations in Table 1 are the first set of kinematic data needed.

The second set of kinematic results needed is the unit flux, or outflow rates, of fluid into the river. These are again calculated for this example flow system by using Eq. (1) and (2) above in Eq. (12) of Paper II. The unit outflow flux rates q in this transient case depend upon both the location along the river bank s in Figures 2 and 3, and time. The values of the flux q are tabulated in Table 2 as a function of both the arrival time T and the outflow location along the riverbank s.

When these kinematic results are obtained, three of the four hydrologic evaluation phases involved in evaluating subsurface pollution problems have been provided. Since only water-coincident contaminants are treated in this paper, the transport analysis is <u>not</u> considered. Therefore, all of the subsurface flow system results are available in Tables 1 and 2, and in Figures 1, 2 and 3 to obtain the arrival distributions for determining the environmental consequences.

THE FLUID LOCATION/ARRIVAL-TIME DISTRIBUTIONS

The contaminated fluid location/arrival-time distribution gives the location where the contaminated fluid will reach the outflow boundary as a function of time; i.e., it is the arrival response at the outflow boundary. It provides the location of contaminated fluid outflow as a function of the arrival time of the instantaneous pulse of traced fluid that departed from the source at time t_0. Three items are particularly important in this definition: (1) it 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 arrival curve is the response of a specific infinitesimal volume of fluid leaving the source;

Table 1. Summary of flow system fluid kinematics for use in location/arrival-time distributions

[1] Pathline designation	Departure time, t_o, yr		[4] Arrival time at river, T, yr	[5] Arrival location at river, s, ft
	[2]From pond	[3]From well		
1	0.00		21.655	-575.4
2	0.00		18.391	-554.1
3	0.00		16.810	-271.5
15	0.00		16.500	1863.3
16	0.00		16.201	2132.9
21	0.00		16.413	2211.6
26	0.00		24.439	2253.7
27		0.00	9.301	1638.2
31		0.00	8.538	2184.7
34		0.00	8.413	2551.7
37		0.00	8.563	2919.2
40		0.00	8.936	3241.0
41		0.00	9.161	3370.2
27		0.50	11.555	1303.6
28		0.50	10.871	1310.1
34		0.50	8,750	2547.5
38		0.50	10.264	3702.1
41		0.50	11.298	3810.6
27		1.00	12.308	1378.4
28		1.00	11.680	1335.3
34		1.00	9.247	2546.1
38		1.00	11.077	3746.5
40		1.00	11.620	3775.8
41		1.00	12.081	3761.1
27		2.00	13.148	1519.5
28		2.00	12.615	1476.7
31		2.00	11.142	1671.8
34		2.00	10.395	2546.2
38		2.00	12.100	21625.4
40		2.00	12.569	21637.4
41		2.00	12.960	21617.4
27		4.00	14.670	1740.5
28		4.00	14.273	1726.6
31		4.00	13.228	1897.4
34		4.00	12.704	2547.5
38		4.00	13.905	3360.3
40		4.00	14.242	3380.6
41		4.00	14.532	3377.9
27		8.00	18.240	2501.0
28		8.00	17.992	2839.5
31		8.00	17.370	2131.7
34		8.00	17.053	2549.0
38		8.00	17.773	3074.3
40		8.00	17.977	3094.7
41		8.00	18.157	3101.2
27		10.00	20.151	2082.3
28		10.00	19.943	2087.2
34		10.00	19.156	2549.3
38		10.00	19.762	2997.4
40		10.00	19.931	3015.5
41		10.00	20.083	3022.4
1	8.00		29.138	-374.8
3	8.00		24.511	61.2
15	8.00		23.424	2134.7
16	8.00		23.397	3000.2
21	8.00		23.977	3743.4
26	8.00		31.355	4399.8

Table 2. Summary of calculated unit fluid outflow rates into the river

[1] Arrival time at river, T, yr	[2] Arrival location at river, s, ft	[3] Unit outflow rate into river, q, gal/min/ft
8.413	2551.7	0.115132
8.5	2250.0	0.115109
8.5	2500.0	0.115100
8.5	2837.0	0.115051
9.0	1780.0	0.114888
9.0	2250.0	0.114934
9.0	2750.0	0.114893
9.0	3287.0	0.114747
9.5	1563.0	0.114685
9.5	2000.0	0.114762
9.5	2500.0	0.114767
9.5	3000.0	0.114680
9.5	3505.0	0.114505
10.0	1437.0	0.114512
10.0	1750.0	0.114585
10.0	2250.0	0.114633
10.0	2750.0	0.114591
10.0	3250.0	0.114463
10.0	3650.0	0.114302
10.5	1350.0	0.114360
10.5	1750.0	0.114456
10.5	2250.0	0.114502
10.5	2500.0	0.114492
10.5	3000.0	0.114408
10.5	3500.0	0.114241
10.5	3750.0	0.114129
11.0	1317.0	0.114235
11.0	1750.0	0.114339
11.0	2250.0	0.114383
11.0	2500.0	0.114373
11.0	3000.0	0.114289
11.0	3500.0	0.114125
11.0	3795.0	0.113993
11.5	1300.0	0.114124
11.5	1500.0	0.114179
11.5	2000.0	0.114262
11.5	2250.0	0.114273
11.5	2500.0	0.114263
11.5	3000.0	0.114180
11.5	3500.0	0.114018
11.5	3793.0	0.113889
12.0	1340.0	0.114039
12.0	1750.0	0.114131
12.0	2250.0	0.114172
12.0	2500.0	0.114162
12.0	3000.0	0.114080
12.0	3500.0	0.113920
12.0	3760.0	0.113808
13.0	1482.0	0.113902
13.0	1750.0	0.113955
13.0	2000.0	0.113983
13.0	2500.0	0.113982
13.0	3000.0	0.113901
13.0	3635.0	0.113691
14.0	1650.0	0.113786
14.0	00.0	0.113829

and (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.

The techniques for obtaining the location/arrival distributions for most transient flow systems are similar to those for steady situations described in previous papers. The only major difference in the transient case is the separate, distinct arrival curve for each departure time t_0. Those special techniques are easily illustrated using the tabular results from the example flow system.

The location/arrival-time curves plotted in Figure 4 are obtained by using the arrival time at the outflow boundary T and the outflow location s, from Columns 4 and 5, respectively, in Table 1. The solid curves in Figure 4 are for the arrival at the river of injected fluid from the well. Figure 4 illustrates the more general situation encountered in transient cases where there is a separate and distinct curve for each departure time. It also attests to the overall generality and simplicity of the arrival distributions and their completeness in summarizing the many facets involved in hydrologic evaluation.

THE FLUID LOCATION/OUTFLOW-QUANTITY DISTRIBUTIONS

The contaminated fluid location/outflow-quantity distribution gives the amount of contaminated fluid outflow at various locations along the interface with man's environment. More specifically, it is the variation of outflow flux as a function of the location where the contaminant or contaminated fluid exudes along 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 flux at each location is specified; and (3) the time-dependence of outflow as a function of location is specified

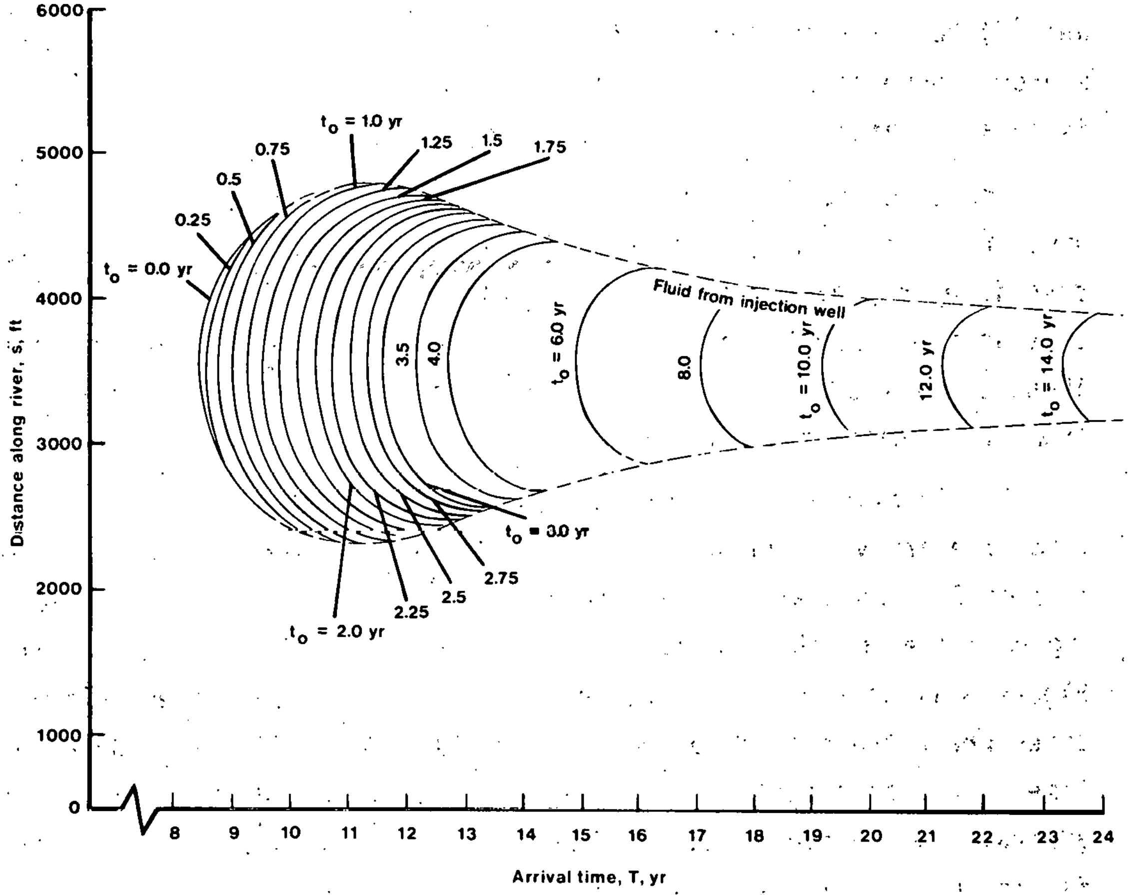


Figure 4. The location/arrival-time distribution of contaminated fluid along riverbank

by successive arrival curves. Accordingly, there is a separate, distinct location/outflow-quantity curve for each and every arrival time at the outflow boundary.

In the example case, the distribution is the outflow rate of contaminant carrying fluid versus the location along the riverbank. The data needed to provide these distributions are available from the fluid outflow results in Table 2. The location s along the river (the outflow boundary) and unit fluid outflow flux rates q for various river arrival times T from Table 2 are plotted as in Figure 5. Figure 5 illustrates that many curves are involved in steady flow cases. With the location/outflow-quantity curves in Figure 5 available, the quantity of fluid carrying contaminants that may interface with the biosphere is readily obtained.

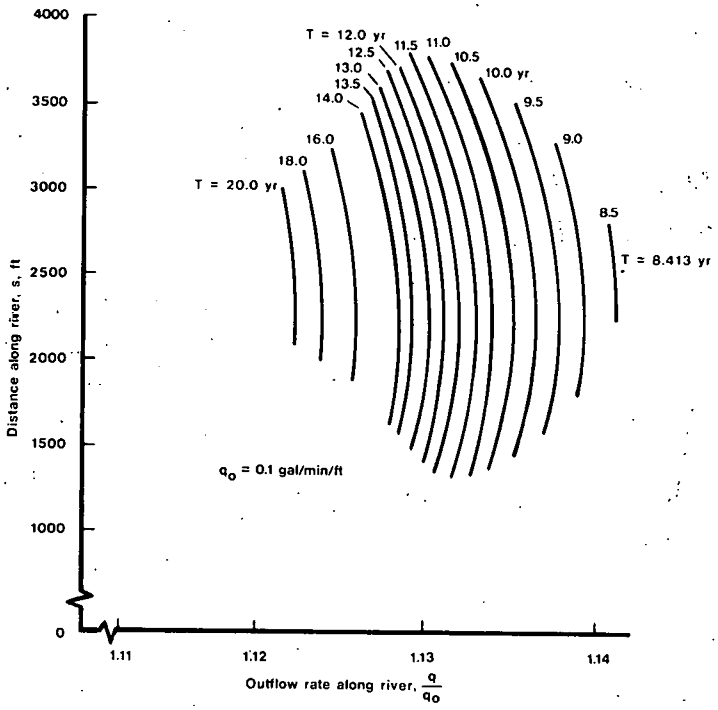


Figure 5. The location/outflow-quantity distribution for contaminated fluid entering the river

THE LOCATION/CONCENTRATION ARRIVAL TIME DISTRIBUTIONS

The location/concentration arrival time distribution provides the location where the contaminant at a particular concentration will reach the outflow boundary as a function of time. It is closely related to and is obtained through use of the fluid location/arrival-time distribution shown in Figure 4. The additional information needed is the input concentration of fluid to the injection well.

The contaminant concentration entering the injection well with passing time is shown in Figure 6 and tabulated values are also given in Table 3. The times t_0 shown in the figure and table are the departure times from the injection well and are, therefore, an integral part of the fluid location/arrival-time curve in Figure 4. In fact, if the concentrations associated with the t_0 values from Table 3 were placed upon the arrival curves in Figure 4, one effectively would have the location/concentration arrival time distribution for the transient example system. This was done in Figure 7 to provide the outflow locations for the various concentrations as a function of the arrival time at the river. This is one of the two final results required for evaluating the environmental consequences.

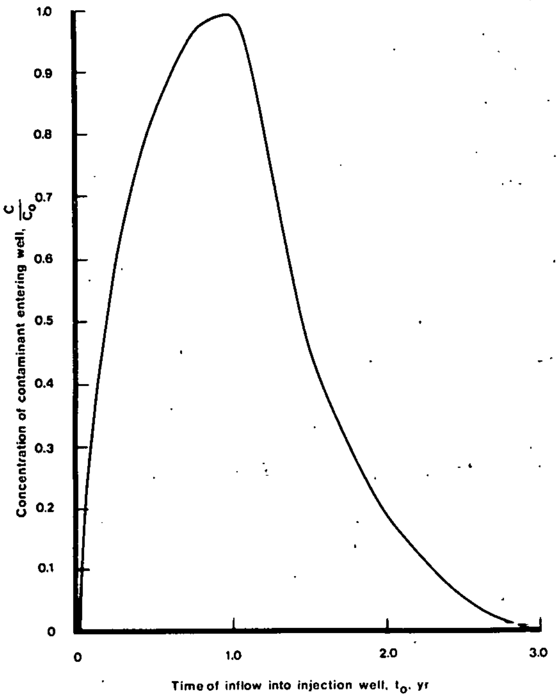


Figure 6. The concentration of contaminant in water entering the injection well

Table 3. The change in concentration of contaminants in injected well water with time

[1] Departure time from injection well, t_0, yr	[2] Concentration of contaminant, $\frac{C}{C_0}$
0.00	0.000
0.25	0.567
0.50	0.833
0.75	0.963
1.00	1.000
1.25	0.963
1.50	0.485
1.75	0.320
2.00	0.202
2.25	0.120
2.50	0.062
2.75	0.025
3.00	0.000

THE LOCATION/ARRIVAL-CONCENTRATION DISTRIBUTION AT THE RIVER

The concentration of contaminants arriving at the river was shown in the last section to vary with the arrival time along the river where the injected fluid emerges. Such time variations are conveniently incorporated into the evaluation of environmental consequence through the location/arrival-concentration curve (distribution). This curve is essentially the same as the location/outflow-quantity curve already described, except the fluid outflow quantity is replaced by the contaminant concentration.

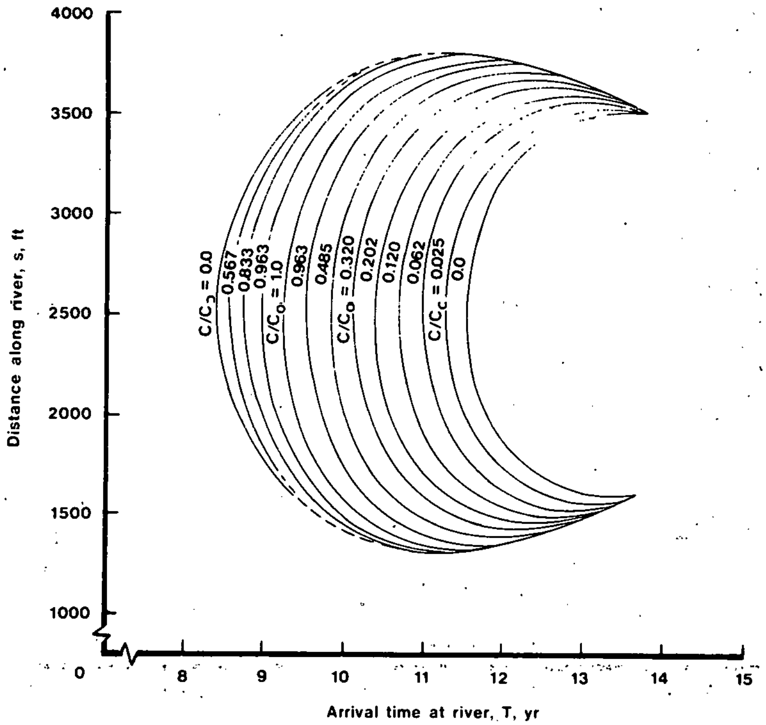


Figure 7. Variation of concentration along outflow boundary as a function of time

The location/arrival-concentration curves for the transient example flow system are given in Figure 8 as obtained from the results in Tables 1 and 3. In Figure 8 the concentrations are shown as a function of the location along the outflow boundary for various arrival times T. The results in Figure 8 represent the same data as in Figure 7 but with the arrival time T appearing as the parameter, whereas C/C_0 served as the parameter in Figure 7. The details for obtaining the results in Figure 8 are described more explicitly in Paper II (Nelson; see discussion of Figures 8 and 9).

Where the flow system is transient and the outflow concentrations are also time-dependent, as in this example, both flow changes and concentration variations with time must be combined. This is done by considering the overall quantity of contaminant outflow as a function of the outflow location.

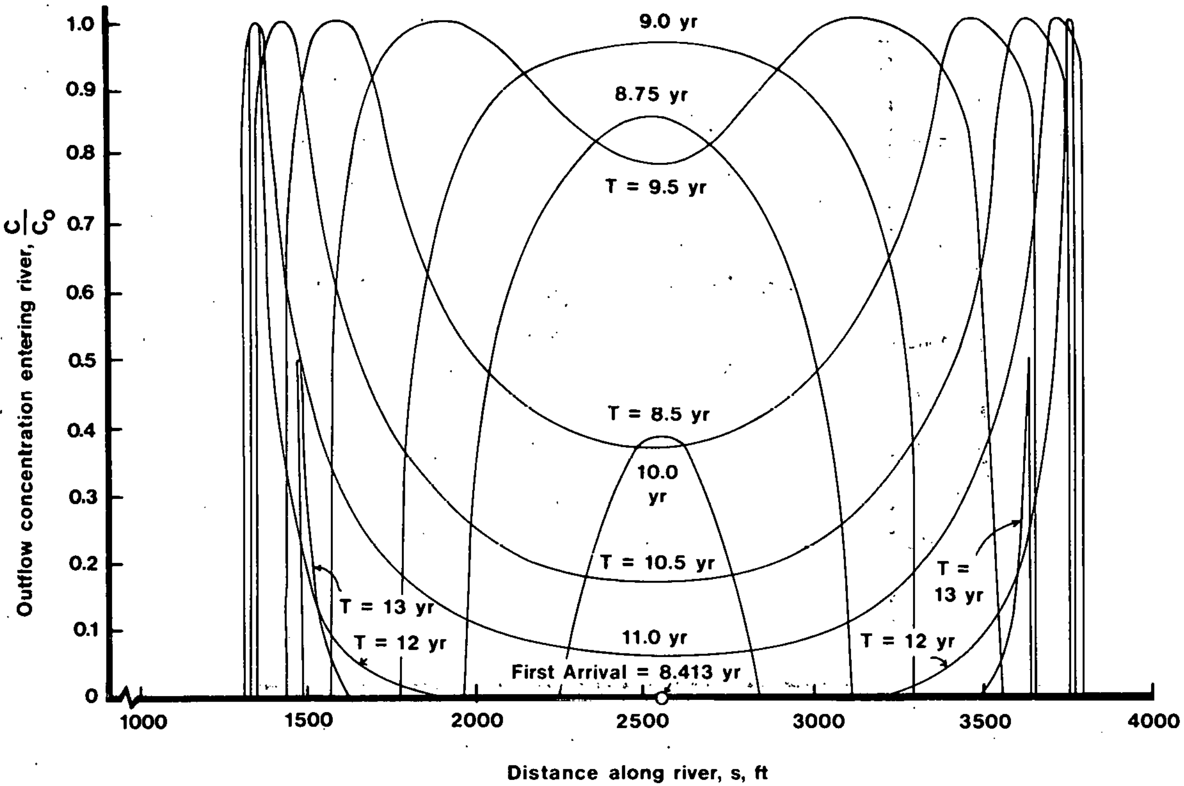


Figure 8. The location/arrival concentration at river for various times

OBTAINING THE LOCATION/CONTAMINANT-OUTFLOW QUANTITY DISTRIBUTION

The quantity or flux rate of contaminant outflow to the river is the product of the concentration and fluid outflow rates at any particular arrival time. Therefore, the location/contaminant-outflow quantity distribution combines the fluid arrival quantities in Figure 5 with the concentration arrival results in Figure 8. In particular, at a given location s and arrival time T, the associated q/q_0 value from Figure 5 is multiplied by the corresponding C/C_0 value from Figure 8 to obtain the contaminant outflow flux $\left(\frac{q}{q_0} \cdot \frac{C}{C_0}\right)$; the same procedure is repeated at other locations and arrival times to provide a complete set of contaminant-outflow results. The complete results are shown in Figure 9 as the final location/contaminant-outflow quantity or flux distribution, which is the result needed to subsequently determine the environmental consequences.

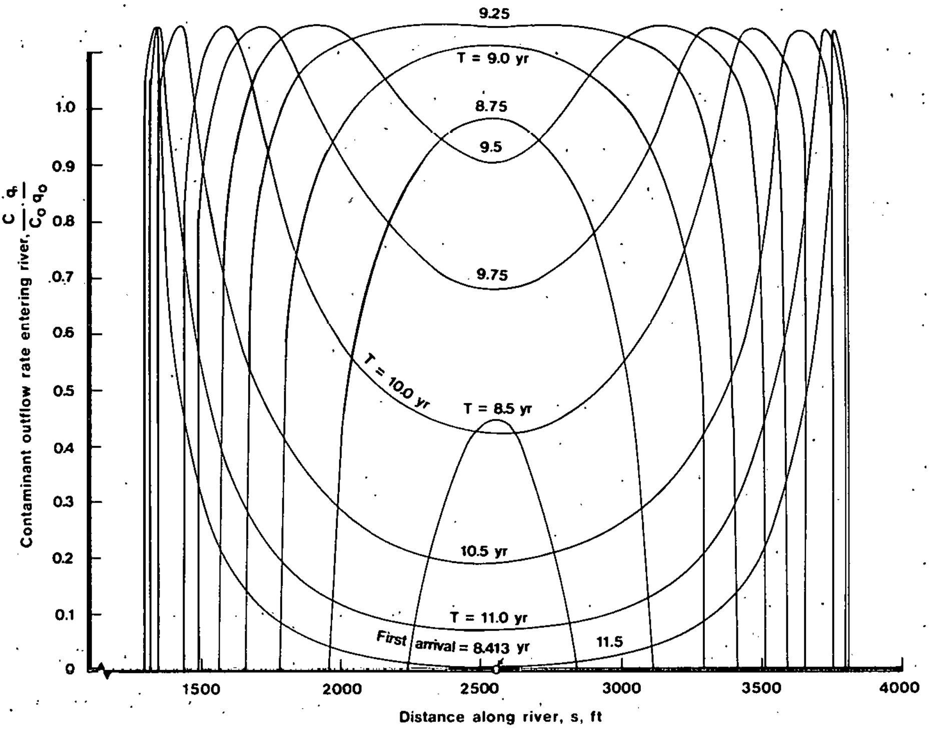


Figure 9. The location/contaminant-outflow quantity distribution entering the river

USE OF THE ARRIVAL DISTRIBUTIONS TO EVALUATE THE ENVIRONMENTAL CONSEQUENCES

The location/arrival-time and location/contaminant-outflow quantity distributions are used together as described in the previous papers to give the potential consequences of contaminants interfacing with the biosphere. Specifically, the integral form of Eq. (14) in Paper II is used, i.e.,

$$W = C_0 q_0 \int_{s_1}^{s_2} \frac{C}{C_0} \cdot \frac{q}{q_0} \, ds \qquad (6)$$

where W is the total contaminant outflow rate in, for example, pounds per minute and the other terms are as previously defined.

At a particular arrival time T, either the location/arrival-time distribution (Fig. 3) or the location/concentration arrival-time distribution (Fig. 7) provides the limits of integration s_1 and s_2 in Eq. (6), while the location/contaminant-outflow flux curves in Figure 9 provide the integrand $\left(C/C_o \cdot q/q_o\right)$, as a function of the location s. For example, at T = 8.5 years, the contaminant outflow rate W to the river is

$$W_T = 8.33(10^{-5}) \int_{2240\text{ ft}}^{2835\text{ ft}} \frac{C}{C_o} \cdot \frac{q}{q_o} \bigg|_{T = 8.5\text{ yr}} ds \tag{7}$$

where the limits in Eq. (7) are the maximum location intercepts from Figure 4 or Figure 7, and the constant C_oq_o was evaluated using item 14 in Figure 1 and the q_o value from Figure 5. Evaluation of the integral gives

$$W_{T = 8.5\text{ yr}} = 0.0147\text{ lb/min} = 0.882\text{ lb/hr} \tag{8}$$

The integral in Eq. (7) is represented graphically simply as the area under the T = 8.5 years curve in Figure 9. In fact, one notices that the integration limits also are provided by the final location/contaminant-outflow quantity curves in Figure 9.

As a second illustration, consider the contaminant-outflow rate at T = 10.0 years; then

$$W_T = 8.33(10^{-5}) \int_{1435\text{ ft}}^{3650\text{ ft}} \frac{C}{C_o} \cdot \frac{q}{q_o} \bigg|_{T = 10\text{ yr}} ds \tag{9}$$

or

$$W_{T = 10\text{ yr}} = 0.1305\text{ lb/min} = 7.83\text{ lb/hr} \tag{10}$$

where again the upper and lower limits are the bounding location ordinates at T = 10 years. In terms of Figure 9, the contaminant outflow rate W in Eq. (10) is simply the area under the T = 10 years curve adjusted to appropriate units, i.e., to pounds of contaminant per minute or hour.

In a similar manner, additional times could be chosen and the appropriate integrals evaluated to provide a complete description of the total outflow rate, or quantity, of contaminant entering the river with passing time. The results of several such evaluations are shown in Table 4 and are plotted in Figure 10 to give the variation of the contaminant outflow rate W with the time T. The outflow rates of contaminated water to the river at the various arrival times during which contaminants are entering the river also are provided in Figure 10.

The rate of contaminant flow into the river in Figure 10 is the second of the two results necessary to completely evaluate the environmental consequences of, in this case, the injection of contaminants at the well. It shows how much contaminant will enter the river with passing time.

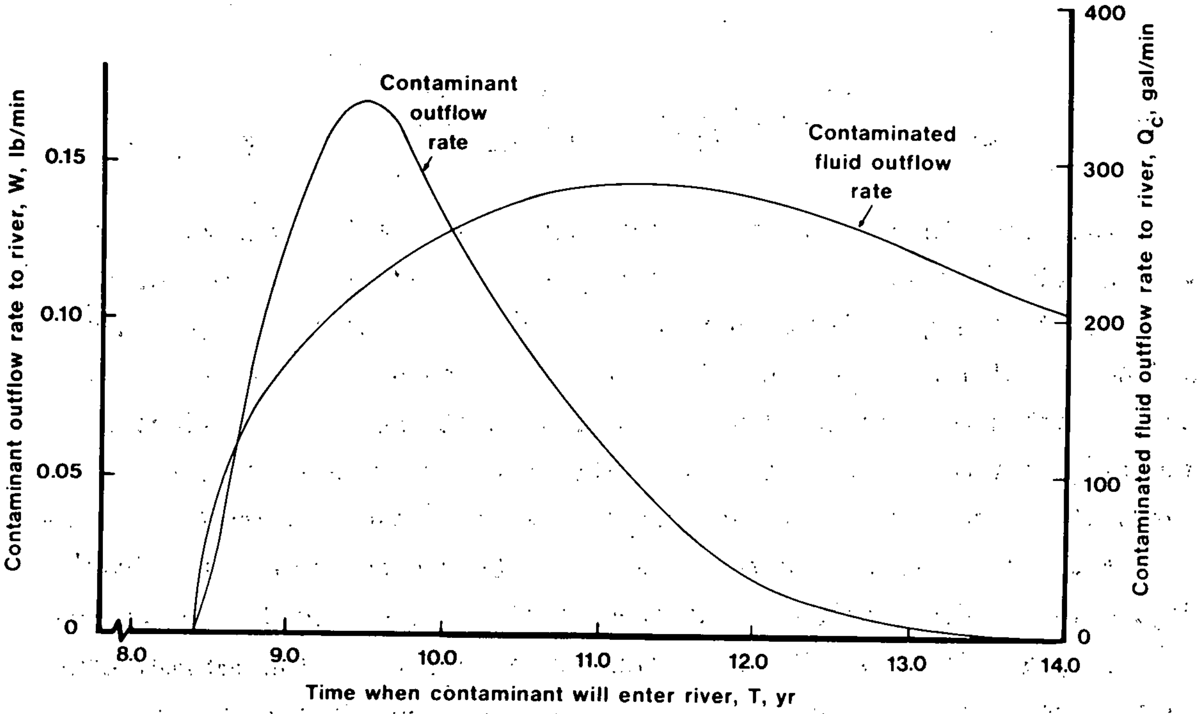


Figure 10. The flow rate of contaminant into river

Table 4. The contaminant outflow rates to the river resulting from injected fluid and contaminants at the well

[1]Time since first contaminant entered injection well, T, yr	Outflow rates to the river		
	Contaminant, W		[4]Contaminated fluid, Q_c
	[2]lb/hr	[3]lb/min	gal/min
8.413	0.00	0.000	0.0
8.50	0.88	0.0147	67.1
8.75	4.54	0.0757	135.0
9.00	7.53	0.1256	173.7
9.25	9.51	0.1585	199.8
9.50	10.10	0.1683	223.3
9.75	9.44	0.1573	238.5
10.00	7.83	0.1305	254.3
10.50	5.56	0.0926	275.3
11.00	3.58	0.0596	284.5
11.50	2.14	0.0357	285.6
12.00	1.07	0.0179	277.2
12.50	0.49	0.0082	263.8
13.00	0.19	0.0031	244.9
13.50	0.05	0.0008	223.9

FINAL RESULTS FOR EVALUATING THE ENVIRONMENTAL CONSEQUENCES

The complete environmental consequences are easily determined at various times by using the results in Figures 7 and 10. From Figure 10 or Table 4, the quantity or outflow rate of contaminant W is provided as a function of time. The additional results needed are provided by Figure 7 which shows the outflow concentrations at specific locations as a function of time. For instance, at the peak inflow rate or at T = 9.5 years after the first contamination entered the injection well, the contaminant outflow rate W to the river is 0.168 pounds per minute, from Figure 10. A description of the concentration is provided by using the T = 9.5 years in Figure 7. Specifically, at 9.5 years the maximum concentration, i.e., $C/C_0 = 1.0$ or $C = 8.33 \times 10^{-4}$ pounds per gallon, is flowing into the river at s = 1940 feet and at s = 3080 feet. These are the locations of maximum outflow concentration, but the location of outflow for any lesser concentration is also available from Figure 7. Occasionally, if still more details were desired for other concentrations at T = 9.5 years, one could utilize Figure 8 where the continuous change in concentration is given as a function of location along the river.

Consideration of a second time, say at T = 13 years when less contamination is entering, illustrates the completeness of results available. From Figure 10 at T = 13 years, the total contaminant outflow rate is 0.0031 pounds per minute and the contaminated water outflow is 245 gallons per minute. Additional results from Figure 7 show that contaminants only enter the river at 13 years for the locations where s is greater than 1480 feet and less than 1620 feet, and where s is greater than 3478 feet and less than 3655 feet. Further detail on the concentration is available from Figure 8 where, if desired, the entire concentration variation with outflow location is shown for T = 13 years.

At any other time the same final results can be obtained by using Figures 7 and 10, and 8 when greater detail for the inflow concentration is desired. In this way the amount and concentration of contaminants entering the river as time passes are provided. With this information, the appropriate river fluid mechanics and domestic, agricultural, or industrial water quality standards can be applied to indicate the environmental consequences of the subsurface pollution problem.

CONCLUSIONS

By combined application of the various location/arrival-time and location/outflow-quantity distributions, the complete results needed to determine the consequences of subsurface pollution can be presented in terms of two figures. The simplicity of the summary results is maintained even when the system involves transient flow and time-dependent input concentrations. Once the arrival results are obtained from the more complicated transient hydrologic analysis, the environmental consequences are available in very simple and direct form. Certainly, these summary results are the facts needed by the decision-maker to choose alternatives or allow, disallow, or require corrective actions based upon the environmental consequences. Thus, results of the type shown in Figures 7 and 10 are the most important information that should be provided for and communicated to the decision-maker. Accordingly, the decision-maker and public control authorities should request or even perhaps require the results of subsurface pollution investigations to be provided in the form of arrival distributions and the resulting simpler summary figures or tabulations. Such an end objective would be accomplished most easily by requesting compliance with the five unified requirements for assuring a complete subsurface evaluation previously proposed (Paper I).

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REFERENCES

Nelson, R. W. Evaluating the environmental consequences of groundwater contamination, I: An overview of contaminant arrival distributions as general evaluation requirements, submitted to Water Resources Res. as Paper I in this sequence.

Nelson, R. W. Evaluating the environmental consequences of groundwater contamination, II: Obtaining location/arrival-time and location/outflow-quantity distributions for steady flow systems, submitted to Water Resources Res. as Paper II in this sequence.

Nelson, R. W. Evaluating the environmental consequences of groundwater contamination, III: Obtaining contaminant arrival distributions for steady flow in heterogeneous systems, submitted to Water Resources Res. as Paper III in this sequence.

Shames, I. H. Mechanics of Fluids, pp. 231-234, McGraw Hill, New York, 1962.