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Evaluating the Environmental Consequences of Groundwater Contamination

MANAGEMENT SUMMARY AND TECHNICAL PAPERS
by R. William Nelson

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FOREWORD

R. A. Deju

This report is part of a program presently sponsored by Atlantic Richfield Hanford Company (ARHCO) to assess the type of environmental information needed by decision-makers and the public to evaluate the environmental impact of a given project.

Environmental impact statements grew out of public concern for environmental quality. These statements evaluate the possible degradation of the environment as a result of human actions. Such statements are supposed to help everyone concerned select those options that will allow optimal use of the environment. An ideal environmental assessment would tell the decision-makers all they need to know to evaluate the consequences of a proposed project. This information must be supplied by technical staff concisely, completely, and with great clarity.

The following series of papers is the result of cooperative studies by personnel from BCS Richland, Inc. and ARHCO exploring ways of summarizing and presenting environmental data. The concept introduced in these papers involves parameters known as "arrival distributions." These quantities define in simple terms how much of a contaminant reaches a specific point at a specific time. We hope these "arrival distributions" will help communicate environmental information effectively to decision-makers and the public.

However, environmental impact statements cannot simply summarize information; they must be active, not passive. Therefore, the "arrival distributions" should be combined with cost-benefit analyses and scenarios depicting the consequences of various actions to allow decision-makers and the public to see all the options prior to implementation of a project. Used in this way, environmental impact statements can be an effective tool for minimizing environmental abuse and maximizing environmental utilization.

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EVALUATING THE ENVIRONMENTAL CONSEQUENCES
OF GROUNDWATER CONTAMINATION

A
Compendium
including:

A MANAGEMENT SUMMARY

and

- I. An Overview of Contaminant Arrival Distributions
as General Evaluation Requirements
- II. Obtaining Location/Arrival-Time and Location/Outflow-
Quantity Distributions for Steady Flow Systems
- III. Obtaining Contaminant Arrival Distributions for
Steady Flow in Heterogeneous Systems
- IV. Obtaining and Utilizing Contaminant Arrival
Distributions in Transient Flow Systems

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EVALUATING THE ENVIRONMENTAL CONSEQUENCES
OF GROUNDWATER CONTAMINATION

A MANAGEMENT SUMMARY

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INTRODUCTION

Environmental impact statements are an important outgrowth of public concern for environmental quality. In these statements, the probable effect on the environment of some proposed or continuing human action is identified and evaluated. Impact statements are intended to help the public and regulatory authorities weigh and select the options that most effectively use the environment for man's benefit, while guarding against any abuse of this privilege. However, if the scientific and technical results of an environmental assessment are not clearly and efficiently communicated to the decision-makers and the public, their effectiveness is greatly reduced. Consequently, the specific information needed by the decision-makers and the public should be presented in a form that can be easily understood and conveniently applied.

A most pressing problem in many environmental assessments is determining the extent of contamination to the biosphere resulting from a

¹This summary was prepared under Project ARC 566, sponsored by the Groundwater Management Section, Research Department, Atlantic Richfield Hanford Company.

given activity. This could result from the planned or accidental release of a contaminant to the environment and its subsequent transport through air, water, or the food chain. In either case, three critical questions need to be raised in the environmental assessment of the problem:

1. Where are the contaminants?
2. When will they arrive at a specific location?
3. How much of the contaminant will be at the point of uptake?

The location of the contaminant is important, since a contaminant isolated from man both now and in the future may represent little hazard, even in rather large quantities. Under other conditions, small amounts of contaminants arriving at critical locations over a short period may involve severe hazard. The problem of location is simplified by concentrating on those places where the contaminants will interface with the biosphere.

The time needed for a contaminant to reach a critical location is also a vital factor. If the arrival is imminent, corrective actions will be required immediately.

Of the three items, the quantity of contaminant present is perhaps most important. Small amounts may be little more than a nuisance, while larger quantities may constitute serious hazards; consequently, the amount of contaminant and its concentration must be known to effectively evaluate the consequences to the environment and the public.

Thus, knowledge of three interrelated factors--the location of the contaminant arrival on the outflow boundary, the arrival time of contaminant at the boundary, and the quantity of contaminant reaching the outflow boundary--is needed to assess the environmental consequences of contamination. When considered together, these three factors provide easily used tools for direct evaluation of environmental consequences. For non-point source discharge problems, these factors are expressed by two quantitative relationships or distributions: the location/arrival-time distribution and the location/outflow-quantity distribution.

INFORMATION NEEDED BY THE DECISION-MAKER

By combined application of location/arrival-time and location/outflow-quantity distributions, the complete results needed to determine the consequences of many pollution problems are available. These distributions are conveniently displayed as two simple summary graphs. Using these summary graphs, one can quantitatively show how much contaminated fluid will interface with man, the location where the contaminant will contact the environment, and the time at which the contaminant will reach the interface location. In short, these are the facts needed by the decision-maker to choose alternatives and allow, disallow, or require corrective action based upon the projected environmental consequences.

A rather simple groundwater contamination problem is used in this summary to introduce the arrival-distribution concepts and illustrate their usefulness in evaluating pollution problems. In the two-dimensional example, contaminated fluid has entered the ground from a deep pond and is gradually flowing toward the river 1.8 miles away, as illustrated schematically in Figure 1. It is the contaminated groundwater entering the river and reaching the biosphere for which the environmental consequences are to be found through the use of arrival distributions.

The example can be carried further by assessing the impact of corrective measures. For instance, we can consider the effectiveness of pumping from a strategically located well, and reintroducing the pumped fluid into the ground through an injection well, both of which are positioned between the pond and the river. Figure 2 illustrates the locations of the wells and their effects on the various flow paths in such a hypothetical situation.

One group of flow paths from the pond is tapped by the pumped well. The pumped water is piped to the injection well and returned to the groundwater flow system. Paths carrying fluid away from the injection well toward the river lie within the shaded area enclosed by the darker pathlines which encompass the injection well. Also, some groups of pathlines bypass the wells altogether and move more directly to the river. Closer examination of figure 2 also shows the ground location

Figure 1. Schematic of the groundwater contamination problem

Figure 2. Schematic of corrective actions for the sample groundwater contamination problem using pumping and injection wells

of the contaminated water front 14 years after the pollution first entered the groundwater from the pond. Changes in the shape of the contaminated front strongly reflect the various pathline groups in the flow system.

COMMUNICATING THE INFORMATION

This brief discussion of the sample problem and Figures 1 and 2 provides an overview of the problem, a first step in assuring effective communication. Such an overview usually represents the end product of several detailed technical evaluations. In fact, the more complicated the pollution problem, the greater the complexities that must be considered to perform a realistic evaluation. But if effective communication with the decision-maker and the public through an impact statement is the technical contributor's paramount goal, then heavy emphasis should be on:

- Providing a clear and concise overview of the problem or system being analyzed.
- Expressing extensive technical results as simple summary relationships.
- Assessing the impact of any needed corrective action.
- Determining costs and benefits for various alternatives.
- Developing an integrated environmental action plan.

The first item involves gathering basic data related to the problem, with emphasis on the proper definition of the problem. Technical personnel must provide a true overview, without excessive detail and technical specifics, yet complete insofar as problem definition is concerned. This information forms the basic data to which the summary relationships are applied.

Summary relationships should be as simple as possible while providing all of the data and results required to assess the environmental consequences of a given action.

An environmental assessment should not be a passive process. Once the assessment is completed, the summary relationships should be used

to assess the impacts of corrective actions, potential scenarios and contingency plans. Such a treatment can form the basis for the cost-benefit studies that are needed to develop a truly integrated environmental action plan. Such an integrated action plan is the optimum way to present environmental information to decision-makers and the public.

This report describes the basis for expressing the needed summary relationships using the examples depicted in Figures 1 and 2. Papers I, II, III, and IV in this compendium treat these examples and a variety of other cases in more detail.

THE LOCATION/ARRIVAL-TIME DISTRIBUTION

The location/arrival-time relationship or distribution is the first of the required summary results. It is shown as the center graph in Figures 3 and 4. Figure 3 depicts the case in which no corrective action is taken; for the case depicted in Figure 4, an injection well and a pumping well are installed. These graphs show the contamination arrival time as a function of location along the riverbank. The location/arrival-time curve quantitatively interrelates the "where" and "when" aspects. These aspects are two of the three final factors required to assess the environmental consequences of a pollution problem.

Several effects of groundwater flow and contaminant transport on the overall system response summary (i.e., the location/arrival-time curve) are seen in Figure 4. The four subcurves of the complete arrival curve (labeled A through D) result from movement of the different groups of flow paths that make up the subflow systems discharging into the river at different locations. Arrival curves are best understood and their irregularities best interpreted in terms of the originating flow system, as illustrated in Figure 4. The location/arrival-time distribution graphs in Figure 4 shows four zones labeled A through D. These zones represent different paths taken by the water (and the contaminant it contains) as follows:

Figure 3. Basic summary results needed to evaluate groundwater contamination problem

Figure 4. Basic summary results required to determine correction actions for groundwater contamination problem

Zone A Seepage from the pond bypassing the injection well

Zone B Pond seepage captured by the pumped well and disposed at the injection well

Zone C Pond seepage bypassing both the injection and pumped wells

Zone D Pond seepage bypassing the pumped well

The positions of the subcurves on the arrival time scale reflect the longer or shorter flow paths and the changing seepage velocities that occur as the contaminant flows along the various paths in the system. The figure illustrates the special relationship between the advancing contamination front (at 14 years) in the flow system and the apparent reversal of the arrival curve form. The reversal occurs because the foremost parts of the advancing front reach the river first and so have the earliest arrival times. Hence, in the arrival curve, these earliest points yield the reversal in curve shape between the front and arrival curve.

The location where the contaminated seepage from the pond will enter the river is provided at any elapsed time ($T-t_0$) by the location/arrival-time curve. Not only is the outflow location of the first contamination leaving the pond at $t_0 = 0$ provided by the curve but also the arrival time for any of the later departures (t_0). The one curve provides all of this information when the flow is steady, as in our example. For a transient system, however, there are as many arrival curves as there are departure times. Each of these arrival curves is considered and used in the same way as the one curve from a steady flow system.

THE LOCATION/OUTFLOW-QUANTITY DISTRIBUTION

The second summary distribution needed is the location/outflow-quantity relationship, which is also illustrated in the bottom graphs of Figures 3 and 4. All of the effects upon flow rates into the river caused

by differences in flow path lengths and movement rates are reflected in the location/outflow curve. In Figure 4 specifically, the lowest groundwater flow rate into the river between zones C and D is caused by the proximity of this location to the pumped well. The highest outflow rates along the bank occur in zones A and B, since these locations of greatest stress in the groundwater flow field are nearest the injection well.

The single curves in Figures 3 and 4 representing the location/outflow distributions are a result of the steady state of the example flow system. In transient systems, several curves (each representing a different arrival time at the river) would make up the outflow quantity distribution. Each of the transient curves is used in the same way as the one curve for the simpler case illustrated here.

The location/outflow quantity distribution summarizes the many interactions in the subsurface system which influence the "where" and "how much" of the pollution problem. In fact, this summary distribution provides a quantitative interrelationship between these two aspects on a single-response basis.

USING SUMMARY RESULTS

The two arrival summaries can be used to determine the quantities of contaminants that may interface with the environment. In our example case, the water enters the ground at a constant rate, but the water entering is contaminated only for the first 300 days or 0.85 years. After that time, no contamination is in the pond water seeping into the ground. The specific location/arrival-time curves for the first contaminated fluid released from the pond at $t_0 = 0$ and for the last of the contaminated fluid leaving the pond at $t_0 = 0.85$ years are plotted in Figure 5. These plotted results are obtained using the t_0 values in the arrival-time curve from Figure 4. In the shaded areas of Figure 5, the concentration entering the river is the same as originated in the pond since there is no dilution by the pumped well. However, the concentration varies with time at the locations where the water from the injection well emerges (see outflow zone B).

Figure 5. The contaminant concentrations of potential interface with man as a function of location and time when using a pumping and injection well.

The changing concentration at the river along outflow zone B is caused by the varying input concentration of the injected water received from the pumped well. The concentration of water pumped from the well changes with time since the contamination front from the pond reaches the pumped well at different times along different flow paths. In particular, contamination moving along the shorter, more direct flow paths reaches the pumped well before the contamination that moves more slowly along the longer flow paths. Accordingly, some contaminated water enters the well from the direct paths and is diluted by the uncontaminated water entering from longer paths.

Use of Figure 4 and the location/arrival curve for the pumped well provides the C/C_0 curves shown in outflow zone B of Figure 5. The first arrival curve from the injection well is for the ratio of outflow concentration to the pond concentration, $C/C_0 = 0$, or for first contaminant arrival. It is followed by the arrival curve for $C/C_0 = 0.613$ and the arrival curve for the peak concentration of $C/C_0 = 0.815$. The

remaining curves are for diminishing concentrations reaching the river; the last curve shown is for $C/C_0 = 0.022$. Figure 5 provides the complete concentration results expected at any location and time.

Figure 5 contains the results needed to answer a variety of questions. For example, it enables one to calculate the amount of contaminant a person fishing at a particular time and location along the riverbank would receive from the groundwater entering the river. By changing the fisherman's location with time, the worst possible dose could be computed also.

The location/arrival-time, location/concentration, and location/outflow-quantity distributions are used together to determine the second group of consequences from contaminants interfacing with man. Specifically, at a given arrival time T the product of the water outflow rates (from the bottom graph in Figure 4) and concentrations from Figure 5 are integrated along the riverbank between the limits of contaminant outflow (shown in the center graph of Figure 4). Other arrival times could be chosen and corresponding integrals evaluated to provide a complete description of the total outflow rate or quantity of contaminant entering the river as time passes. The results of such evaluations are plotted in Figure 6 as the solid curve to give the variation of the contaminant outflow rate, W , with the river arrival time T . The dashed curve in Figure 6 represents the outflow rates of contaminated water to the river when the pumped and injection wells are not in use.

The flow rate of contaminants into the river in Figure 6 is the second of the two final results needed to completely evaluate the environmental consequences of the contaminants entering the pond. It shows directly how much of the contaminant will enter the river with passing time.

Note that the effect of the injection and pumping wells is to reduce the total amount of contaminant entering the river at the onset of the operation and to spread contaminant flow into the river at later times.

Figure 6. Outflow rate of contamination entering river from pond

Thus, a system can be designed so that at no time does the total amount of contaminant entering the river exceed the allowable limit.

SUMMARY AND CONCLUSIONS

Environmental consequences or impacts are most effectively and efficiently communicated by:

- Blending extensive technical results and reducing them to simple summary relationships; i.e., the arrival distributions
- Focusing on the arrival distributions as the central theme of communication efforts
- Determining quantitative consequences or impacts to the biosphere through use of the arrival distributions.

Appropriately applied, these principles can reduce a voluminous impact statement on subsurface pollution to a few pages that are directly useful to decision-makers and the public.

The arrival distributions are the key to this process. Specifically, by using the basic location/arrival-time and location/outflow-quantity distributions, the complete results needed to determine the consequences of subsurface pollution problems can be presented in simple form. The summary results remain simple even when the analysis involves complicated geologic and hydrologic effects. Once the arrival results are obtained from the more complicated analysis, the environmental consequences can be assessed in very simple and direct form. These summary results are the facts the decision-maker needs to choose alternatives or to allow, disallow, or require corrective actions based upon the environmental consequences. Accordingly, decision-makers and public control authorities would be well advised to request or perhaps even require subsurface pollution investigations to provide the simpler arrival distributions and the resulting summary of contamination consequences.

ACKNOWLEDGMENTS

The author gratefully acknowledges the worthwhile discussions with personnel of the Groundwater Management Section of Atlantic Richfield Hanford Company during preparation of this summary. Also, appreciation is expressed to Ms. Lea LaZelle, BCSR technical writer, for her effort in editing and bringing the document to finished form.

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.

¹This paper is based partially upon work performed under Atomic Energy Commission Contract (45-1)-1820 and United States Energy Research and Development Administration Contract E(45-1)-2320.

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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

²The 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; Hackett, 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 $\pm s$ 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, $T-t_0$, yr	[3] Location along river bank from center of flow, $\pm s$, ft	[4] Outflow rate, q , gal/min/ft	[5] Strontium** ion arrival time at river bank, T_s-t_0 , 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

*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

$t_0 = 0.85$ 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.:

$$Q_T = 15.35 \text{ yr} = \int_{-1000 \text{ ft}}^{1000 \text{ ft}} q \, ds = 228.06 \text{ gal/min} \quad (1)$$

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:

$$Q_T = 17 \text{ yr} = \int_{-1790 \text{ ft}}^{-1500 \text{ ft}} q \, ds + \int_{1500 \text{ ft}}^{1790 \text{ ft}} q \, ds = 64.55 \text{ gal/min} \quad (2)$$

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:

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

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).

IV.1

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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EVALUATING THE ENVIRONMENTAL CONSEQUENCES
OF GROUNDWATER CONTAMINATION

II. Obtaining Location/Arrival-Time and Location/Outflow-
Quantity Distributions for Steady Flow Systems

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ABSTRACT

A steady, two-dimensional flow system is used to demonstrate the application of location/arrival-time and location/outflow-quantity curves in determining the environmental consequences of groundwater contamination. The subsurface geologic and hydrologic evaluations needed to obtain the arrival results involve a sequence of four phases: system identification, new potential determination, flow systems kinematics, and contaminant transport analysis. Once these phases are completed, they are effectively summarized and easily used to evaluate environmental consequences through the arrival distributions.

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INTRODUCTION

New location/arrival-time and outflow-quantity distributions offer an optimal means of evaluating environmental consequences of subsurface pollution. The first paper in this sequence presented an overview of these distributions. This and subsequent papers indicate the technical basis and natural evolution of the distributions using hydrologic results.

In this paper, those methods applicable to steady, two-dimensional flow systems in homogeneous materials but with complicated flow geometry will be described. The natural development of arrival distributions from the various hydrologic evaluations is considered first in general terms. Emphasis is then narrowed to the techniques used in obtaining arrival results. An example illustrates several steps necessary to arrive at the final contaminated fluid location/arrival-time distribution and the location/outflow-quantity distribution. Once these are determined, the amount of contaminants emerging along the outflow boundary (i.e., the potential interface with man) as a function of time can be calculated.

THE TECHNICAL BASIS FOR ARRIVAL DISTRIBUTIONS

The contaminant arrival distributions have their origin and depend directly upon the many measurement and evaluation capabilities of subsurface hydrology. This is essentially axiomatic since arrival distributions simply provide the tools which summarize final hydrologic results needed for environmental evaluation. Depending on the pollution problems involved, the entire range of subsurface technology may be involved. This discussion classifies the evaluation process into four basic phases, each of which will be considered in general terms:

- System Identification
- New Potential Determination
- Flow System Kinematics
- Contaminant Transport Analysis

Together, these phases provide the technical basis for the contaminant arrival distributions.

SYSTEM IDENTIFICATION

System identification involves the determination and measurement of those physical characteristics pertinent to evaluating the subsurface system of fluid flow and contaminant transport (Phillipson, 1971). It includes measurements and evaluations of the physical extent of the groundwater basin or sub-basins, any groundwater connection with surface streams, recharge areas, groundwater divides, etc. Determining the properties of the porous material (e.g., capillary conductivity and hydraulic conductivity variation throughout the region, porosity variations, and geochemical and exchange characteristics) is also a vital part of the system identification phase (Coats, 1963; Prudhumme, 1967).

The identification phase is probably the most important, and perhaps the most difficult, phase to adequately yet economically complete. Accurate and representative data are vital. With good basic data, excellent credibility is possible for the final results, whereas inadequate identification often leaves doubts and unanswered questions. Although accuracy and realism are primary objectives, the identification costs must be kept within economical limits. Since measurement access involves well drilling and predominantly remote observations, the costs of getting adequate subsurface data are high.

During this last decade, increasing research and development effort has been directed to this basic identification problem. Significant progress has occurred by using more complete and sophisticated analysis of specific field data taken over large regions. This is a distinct contrast to the approach of using many measurements on small samples.

The dissipation methods of obtaining hydraulic conductivity distributions in large heterogeneous groundwater systems are good examples of the newer developments in system identification (Nelson, 1969; Emsellem, 1971). The traditional methods of determining hydraulic conductivity primarily involve individual pumping tests or related point observation

methods. Though moderately accurate when very carefully executed, they are far too costly to utilize extensively over large regions since so many wells and expensive tests are required. The new dissipation methods require only a limited number of point pumping tests, but mainly rely on a comprehensive evaluation of groundwater potential data over the entire region to determine the hydraulic conductivity distribution. Basic theory and more intricate analysis of the data are required with the new method, yet the actual field measurement of the groundwater potential is simpler, more accurate and much cheaper than the traditional pumping test methods.

As more of these detailed, extensive methods of measurement and determinations are developed and used, determination of the subsurface characteristics will become more economical and more accurate. Improved system identification will provide a sounder basis for the next phase--determining the new groundwater potential distribution.

NEW POTENTIAL DETERMINATION

Determination of new potential energy variations involves all the steps and methods useful in finding the expected groundwater potential throughout the particular regions of interest. It includes predicting changes in partially saturated flow in the vadose zone and saturated flow beneath the water table. These changes may result from proposed management practices or simply from natural trends in the subsurface flow regime. In any case, the new potential energy distribution is obtained through setting up and solving appropriate well-posed boundary value problems for either isothermal, nonisothermal, saturated, partially saturated, or multiphase flow systems (Bredehoeft, 1970; Freeze, 1971; Pinder, 1972).

The boundary value problem interrelates all of the pertinent physical variables measured during system identification and, when solved, gives the new groundwater potential resulting from any and all changes to the flow system. All of the system variables form a unique boundary

value problem, either through the partial differential equation or the boundary conditions which include initial conditions. Once the partial differential equations are solved and all of the boundary conditions satisfied, the new potential distribution is the meaningful result needed in this phase of the complete evaluation.

The new potential energy patterns may be determined in a variety of ways: direct mathematical forms, numerical digital computations, analog simulations, or, in some cases, measurements on constructed models. However, none of these is always the best approach for all problems. Continuing efforts to find more generally applicable and better solution methods are providing additional promising techniques (Javandel, 1968; Finlayson, 1966, 1969, 1972). As these become more widely used, greater solution capacity and efficiency can be expected in this vital area of new potential determination.

FLOW SYSTEM KINEMATICS

Flow system kinematics involves all the analysis and evaluation capability necessary to determine the geometry of fluid motion from the new potential distribution in the subsurface flow system (Truesdell, 1960). Specifically, the flow paths of fluid particles, the travel times of the advancing fronts along those pathlines, and the quantity of fluid flux at particular places in the system are the end objectives.

The results from the system identification and new potential determination phases enable obtaining the kinematic path functions, stream functions, and streak functions for subsurface systems. The identification provides the saturation, capillary or hydraulic conductivity and porosity distributions which, when combined with the new potential distribution, give the velocity of fluid throughout the flow system. The three kinematic functions, i.e., path functions, stream functions and streak functions, have defining sets of differential equations arising from the hydraulic conductivity, saturated permeability, porosity, saturation, and potential distributions (Nelson, 1969).

The path functions require the conductivity, porosity and potential to define the set of characteristic differential equations. These are to be solved simultaneously with appropriate initial conditions to yield the subsurface pathlines and rates of fluid advance. The path function itself gives the loci of points (representing a particular contaminant front) as a function of time for those particular fluid particles which occupied a given spatial array at an initial or time. For environmental evaluations, the most important locations are the contaminated fluid outflow boundaries where pollutants interface with man's environment. The pathlines and functions provide:

- The contaminated fluid arrival locations on the outflow boundary
- The arrival time of the contaminated fluid at the outflow boundary

Thus, the kinematic path function provides two of the three factors required to obtain the arrival distributions for subsurface fluids and for fluid coincident contaminants. The third factor, that of fluid quantity, comes from the stream function.

The stream functions use the permeability distribution from the system identification phase and the new potential distribution to define the set of characteristic differential equations (Nelson, 1969). Solution of these equations subject to appropriate boundary conditions provides the flux distribution throughout the subsurface flow system. The stream function is evaluated along the outflow boundary to determine the quantity of contaminated fluid that will interface with man, the third factor needed to obtain complete arrival distributions.

In some transient flow systems the kinematic streak function is very useful (in fact, necessary) to complement the path function in determining the arrival location and arrival time. The streak function boundary and initial conditions are considerably more involved since the streak function is a natural extension of the path function. Specifically, the characteristic form of a streak line is the loci of all fluid

particles that have or will pass through a given point in space. Use of streak functions will be considered further when the more complicated transient systems are discussed.

In general, flow system kinematics utilizes the permeability, porosity and new potential distributions to provide the outflow location, time and quantity of contaminated fluid that make up the arrival distributions. Either the path functions or the streak functions provide the arrival locations and time at the outflow boundary, whereas the stream function provides the outflow quantity.

For fluid coincident contaminants, or those which essentially move with the fluids, the evaluation need not continue beyond the flow system kinematics phase. However, if there are exchange or geochemical reactions of the individual chemical species being transported by the subsurface flow system, the contaminant transport analysis phase is required. The system kinematics then becomes an important input which completely describes the transporting fluid.

CONTAMINANT TRANSPORT ANALYSIS

The contaminant transport analysis involves all of the additional formulations and evaluations necessary to incorporate the effects of dispersion, contaminant exchange, and other geochemical reactions with the porous material (Cearlock, 1966; Helgeson, 1968, 1969, 1970; Schwartz, 1973), including all important chemical or biological interactions between individual constituents of groundwater. The subsurface flow system analysis provides the fluid movement effects. These are coupled to the interactions with the porous material and the reaction of individual constituents to determine the transport equations for the mixture of contaminants. The addition of appropriate initial and boundary conditions for the transport problem provides a predictive capability. The results are the arrival locations, arrival times, and outflow quantities for each constituent involved in the transport evaluation.

This discussion has presented an overview, devoid of equations and excessive details, of the technical basis for the arrival distributions and outlined the pertinent hydrologic analysis steps. A detailed consideration of specific cases in this and subsequent papers should

demonstrate the insight needed to obtain arrival distributions from hydrologic results.

ARRIVAL DISTRIBUTIONS FOR STEADY, TWO-DIMENSIONAL FLOW SYSTEMS

Arrival distributions for steady, two-dimensional flow systems are considered first to minimize the discussion necessary for the system identification and potential determination phases of the hydrologic evaluation. The emphasis is on the flow kinematics phase and more particularly on the specifics of obtaining contaminant location/arrival-time and location/outflow-quantity distributions from the hydrologic results. These methods are best described and illustrated by example.

EXAMPLE SYSTEM IDENTIFICATION

The two-dimensional example involves steady lateral flow in a homogeneous and isotropic porous slab of constant thickness and of infinite lateral extent. The combined flow system includes a uniform lateral flow altered by flow from a completely penetrating cylindrical pond, a pumped well, and an injection well. In effect, the porous material is idealized to a homogeneous slab. The potential distribution is moderately simple, but the flow system kinematics provides a good illustration of a variety of the techniques needed to obtain and utilize arrival distributions. The specific flow system parameters for the example case are summarized in Figure 1.

EXAMPLE POTENTIAL DISTRIBUTION

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 source and positive doublet (Shames, 1962) centered at the origin to represent outflow from the completely penetrating cylindrical pond. The pumped well and injection well are superimposed as a point sink and source, respectively, to yield an expression for the overall groundwater

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 pumped well) = 7000 ft
10. y_1 (y-coordinate of pumped well) = -1000 ft
11. Q_1 (rate pumped from well) = $-1.5(10^7)$ ft³/yr
12. x_2 (x-coordinate of injection well) = 4000 ft
13. y_2 (y-coordinate of injection well) = 1500 ft
14. Q_2 (rate injected into well) = $1.5(10^7)$ ft³/yr
15. C_o (input concentration to pond) = $4.164(10^{-5})$ lb/gal

Figure 1. Parameters for the sample flow system

potential throughout the slab.

Specifically:

$$\phi = H'H_0 - Ux + \frac{U(r_0)^2 x}{(x^2 + y^2)} - \frac{H'H_0}{\ln\left(\frac{R}{r_0}\right)} \ln\left(\frac{\sqrt{x^2 + y^2}}{r_0}\right) - \sum_{j=1}^{j=N} \frac{m_j}{2\pi} \ln \sqrt{\frac{(x - x_j)^2 + (y - y_j)^2}{(x_j^2 + y_j^2)}}, \quad N=2 \quad (1)$$

where all the variables and parameters are defined in the notation section at the end of the paper.

The potential, ϕ , is defined by Eq. (1) in the region for all $(x^2 + y^2) > r_0^2$ except at the points with coordinates x_j and y_j and satisfies the Laplace equation describing flow in the homogeneous isotropic slab. The potential, ϕ , also satisfies the boundary conditions that $\phi = H'H_0 \pm \epsilon$ when $x^2 + y^2 = r_0^2$; and $\phi = 0 \pm \epsilon'$ when $x^2 + y^2 = R^2$. The wells are singularities of strength m_1 and m_2 in the x - y plane at points x_1, y_1 and x_2, y_2 respectively. It can be shown that the ϵ and ϵ' are negligible if

$$\frac{r_0^2}{(x_j^2 + y_j^2)} < 0.01 \quad \text{and} \quad \frac{x_j^2 + y_j^2}{R^2} < 0.7.$$

The example case is well within the approximation limits; hence, Eq. (1) provides the potential distribution for subsequent use in determining the flow system kinematics.

EXAMPLE FLOW SYSTEM KINEMATICS

The flow system kinematics provides the pattern or geometry of flow in the subsurface system. The pathlines for individual fluid particles through the flow system provide the points of emergence at outflow boundaries. These locations and the arrival time of

fluids at outflow boundaries are determined by the path function. The stream function gives the flux rate at the outflow boundary as well as throughout the entire flow system. Together, the path function and stream function provide all the results needed for the arrival distributions for fluid coincident contaminants in steady flow systems.

FLOW PATHS AND TRAVEL TIMES

(1) The characteristic equations for the path function are most useful in generating the flow paths and obtaining the travel times. They come directly from the definition of the macroscopic pore velocity, $\underline{v}$, utilizing Darcy's Law. That is:

$$\underline{v} = - \frac{K_0}{P} \nabla \phi \quad (2)$$

or by components using Eq. (1),

$$\begin{aligned} \frac{dx}{dt} = & \frac{K_0 U}{P} \left\{ 1 - \frac{r_0^2}{x^2 + y^2} \left[1 - \frac{2x^2}{x^2 + y^2} \right] \right\} + \frac{K_0 H' H_0}{P \ln\left(\frac{R}{r_0}\right)} \left(\frac{x}{x^2 + y^2} \right) \\ & + \sum_{j=1}^{j=N} \frac{K_0 m_j}{2 \pi P} \left[\frac{x - x_j}{(x - x_j)^2 + (y - y_j)^2} \right], \quad N = 2 \end{aligned} \quad (3)$$

and

$$\begin{aligned} \frac{dy}{dt} = & \frac{2K_0 U}{P} \left\{ \frac{(r_0)^2 xy}{[x^2 + y^2]^2} \right\} + \frac{K_0 H' H_0}{P \ln\left(\frac{R}{r_0}\right)} \left[\frac{y}{x^2 + y^2} \right] \\ & + \sum_{j=1}^{j=N} \frac{K_0 m_j}{2 \pi P} \left[\frac{y - y_j}{(x - x_j)^2 + (y - y_j)^2} \right], \quad N = 2 \end{aligned} \quad (4)$$

The contamination departs from the pond wall at t_0 ; i.e.,

$$x(t_0) = x_0 \quad (5)$$

and

$$y(t_0) = y_0 \quad (6)$$

where

$$(x_0)^2 + (y_0)^2 = r_0^2. \quad (7)$$

Simultaneous solution of Eq. (3) and (4) using the initial conditions in Eq. (5) and (6) is accomplished numerically to yield pathlines and travel times to the pumped well or to the remote river boundary. The calculated results using a fourth order Runge Kutta solution scheme are shown in Figure 2 and summarized in Tables 1 and 2.

STREAM FUNCTION AND OUTFLOW BOUNDARY FLUXES

The flux or fluid flow rate at any outflow boundary is available from the stream function, which is simply the complex conjugation of the potential expressions used in Eq. (1). Upon superposition of the simple basic flows, the stream function is:

$$\begin{aligned} \frac{Q_i}{Q_0} = & \frac{U \ln\left(\frac{R}{r_0}\right)}{2 \pi H_0} y + \frac{U r_0^2 \ln\left(\frac{R}{r_0}\right)}{2 \pi H_0} \left(\frac{y}{x^2 + y^2} \right) + \frac{H'}{2 \pi} \arctan\left(\frac{y}{x}\right) \\ & + \sum_{j=1}^{j=N} \frac{m_j \ln\left(\frac{R}{r_0}\right)}{4 \pi^2 H_0} \left[\arctan\left(\frac{y - y_j}{x - x_j}\right) - \arctan\left(\frac{-y_j}{r_0 - x_j}\right) \right], \quad N = 2 \quad (8) \end{aligned}$$

where:

$$Q_0 = \frac{2\pi D_0 K_0 H_0}{\ln\left(\frac{R}{r_0}\right)} \quad (9)$$

and in this paper, $H' = 1$ and $N = 2$.

Figure 2. The flow pattern of contaminated groundwater from the pond toward the river with a pumped and injection well

Eq. (8) is used to determine the cumulative flow rate for two outflow boundaries of interest in the example flow system. The first is the inflow around the periphery of the pumped well and the other is the groundwater flow entering the river. The cumulative inflow values Q_i/Q_0 are obtained by substituting the x, y coordinates, where the pathlines intersect the well screen, into Eq. (8). These values are given in Column 4 of Table 1 for subsequent use.

Table 1. Summary of flow system kinematics for the example two-dimensional case (see Figure 2)

[1] Pathline designation (See Figure 2)	Arrival time ($T - t_0$) at		[4] Cumulative flow rate, Q_1/Q_0	[5] Arrival location on outflow boundary, s, ft	[6] Boundary outflow rate,** q, gal/min/ft
	[2] Pumped well, yr	[3] River, yr			
19		18.778	0.514	181.6	0.104359
19-A-20		18.490	0.519	202.0	0.104334
19-B-20		17.933	0.531	259.6	0.104269
19-C-20		17.469	0.548	334.7	0.104194
20		17.408	0.507	347.1	0.104182
20-A-21		17.072	0.569	430.5	0.104114
21		16.574	0.618	648.4	0.104012
22		16.508	0.640	748.3	0.104005
23		16.740	0.664	857.7	0.104031
23-A-24		16.926	0.669	877.5	0.104039
23-B-24		17.488	0.673	897.3	0.104048
23-C-24	11.181		0.678	Pumped well	
23-D-24	10.781		0.682	Pumped well	
23-E-24	10.556		0.687	Pumped well	
24	10.425		0.691	Pumped well	
25	9.837		0.719	Pumped well	
26	9.475		0.750	Pumped well	
27	9.212		0.782	Pumped well	
28	9.022		0.816	Pumped well	
29	8.897		0.851	Pumped well	
30	8.840		0.887	Pumped well	
31	8.856		0.925	Pumped well	
32	8.962		0.962	Pumped well	

Table 1. Contd.

[1] Pathline designation (See Figure 2)	Arrival time ($T - t_0$) at		[4] Cumulative flow rate, Q_i/Q_0	[5] Arrival location on outflow boundary, s, ft	[6] Boundary outflow rate,** q , gal/min/ft
	[2] Pumped well, yr	[3] River, yr			
1	9.212		0.0000	Pumped Well	--
2	10.225		0.0378	Pumped Well	--
2-A-3*	10.744		0.0432	Pumped Well	--
2-B-3		16.083	0.0453	921.7	0.10405
2-C-3		15.670	0.0528	955.5	0.10408
2-D-3		15.483	0.0603	989.1	0.104105
2-E-3		15.365	0.0678	1022.5	0.104131
3		15.282	0.0726	1055.9	0.104161
4		15.081	0.121	1220.4	0.104354
5		15.503	0.148	1397.3	0.104642
6		15.423	0.278	1940.3	0.105947
7		15.885	0.332	2161.6	0.106596
8		16.090	0.349	2225.3	0.106789
9		16.336	0.364	2283.7	0.106967
10		16.654	0.378	2335.8	0.107126
11		17.214	0.391	2378.0	0.107255
12		17.310	0.404	4010.0	0.111252
13		17.202	0.415	4054.9	0.111319
14		17.270	0.425	4098.0	0.111381
15		17.396	0.435	4138.1	0.111437
16		17.556	0.443	4174.8	0.111487
17		19.029	0.478	4331.3	0.111680
18		23.106	0.496	88.2	0.104479
18-A-19		20.268	0.502	122.3	0.104433
18-B-19		19.204	0.509	157.8	0.104483

*This pathline designation indicates there are five pathlines A, B, C, D, and E between pathlines 2 and 3, etc. Pathlines with alphabetic designations are not plotted in Figure 2.

**The boundary outflow rates in this column are, at some points in the manuscript, made dimensionless through dividing by $q_0 = 0.1$ gal/min/ft.

Table 2. Summary of flow system kinematics for injected-well water

[1] Pathline designation (See Figure 2)	Injection well		[4] Cumulative flow rate, Q_i/Q_I	[5] Arrival location at river s, ft	[6] Boundary outflow rate,** q, gal/min/ft
	[2] Departure time, yr	[3] River arrival time $T - t_o$, yr			
11-A-33*	8.84	19.711	0.0000	2380.6	0.107263
33	8.84	18.333	0.1498	2625.6	0.108009
34	8.84	18.320	0.1567	2637.1	0.108044
35	8.84	18.150	0.2051	2715.8	0.108278
36	8.84	18.020	0.2737	2827.3	0.108603
37	8.84	17.890	0.3564	2961.2	0.108980
38	8.84	17.805	0.4499	3112.1	0.109386
39	8.84	17.775	0.5478	3269.5	0.109783
40	8.84	17.795	0.6465	3427.6	0.110153
41	8.84	17.870	0.7398	3576.6	0.110475
42	8.84	18.015	0.8230	3709.1	0.110737
43	8.84	18.170	0.8920	3818.7	0.110938
44	8.84	18.352	0.9404	3895.5	0.111069
45	8.84	18.376	0.9476	3906.9	0.111088
45-A-12	8.84	18.755	0.9989	3990.0	0.111221

*This pathline designation indicates pathline A is located between pathlines 11 and 33 but is not shown in Figure 2.

**The boundary outflow rates in this column are, at some points in the manuscript, made dimensionless through dividing by $q_0 = 0.1$ gal/min/ft.

The cumulative flow rate into the river, i.e., the total flow across this important outflow boundary, is given by Eq. (8) through equating

$$x = X \quad (10)$$

and

$$y = s - 2000 \text{ (ft)} \quad (11)$$

where X is the distance to the river and s is the y -coordinate of the point where the particular pathline reaches the river. Again, the results are tabulated for each pathline as Column 4 in Tables 1 and 2. By the fundamental definition of stream function, Q_i/Q_0 provided in Eq. (8) is a cumulative flow rate with zero being any point on the streamline which passes through the point $x = r_0$, $y = 0$.

At the river, the variation of the groundwater unit outflow fluxes along the river rather than the cumulative stream function values is needed and can be calculated using:

$$q = P \frac{dx}{dt} \quad (12)$$

The equation most useful for direct calculation of q is obtained by first substituting the resulting expression for $\frac{dx}{dt}$ into Eq. (12). The unit outflow rates along the river bank were calculated using Eq. (12) and are given in Column 6 of Tables 1 and 2.

The calculated kinematic flow results are summarized in Tables 1 and 2 with the major flow pattern results plotted in Figure 2. In particular, the flow paths and isochronal lines for the advancing contaminated front from the pond toward the river, approximately 1.85 miles away, are illustrated. The contaminated fluid front originating at the pond moves outward in ever-elongating arcs bypassing the injection well on both sides, i.e., pathlines 12 through 17 and 3 through 11. Between pathlines 24 and 2 (including 32, etc.) the contaminated pond outflow is intercepted by the pumped well. The intercepted water is piped to the injection well and reintroduced into the flow system for ultimate arrival at the river between pathlines 33 and 45. The

remaining fluid from the pond between pathlines 18 and 23 does not flow into the pumped well, but proceeds directly to the river.

All of the flow system kinematic results needed to obtain the arrival distributions are available in Tables 1 and 2. The first three of the four overall hydrologic evaluation phases summarized previously and involved in evaluating subsurface problems have been provided. Since, for pedagogical reasons, only water coincident contaminants are considered in this paper, the transport analysis is not required. Thus, all of the subsurface flow system results are available in Tables 1 and 2 and Figures 1 and 2 to obtain usable arrival distributions for determining environmental consequences.

LOCATION/ARRIVAL-TIME DISTRIBUTIONS

Those techniques used to derive meaningful location/arrival-time distributions for many steady, two-dimensional flow systems are illustrated by using the tabular and graphical results of the example flow system. The location/arrival-time distribution is obtained by using the arrival time ($T - t_0$) and outflow location (s) from Columns 3 and 5, respectively, in Tables 1 and 2 as plotted in Figure 3. The seeming multiplicity of curves in the figure is a natural consequence of the several interacting parts of the flow system (see Figure 2). For instance, the part of the location/arrival-time curve in Figure 3 labeled "pathlines 33-45" includes all of the pond fluid intercepted by the pumped well that was reinjected and that later arrived at the river. The other three labeled parts of the curves represent the pond fluid that bypassed the wells by different routes to finally arrive at the river.

LOCATION/OUTFLOW-QUANTITY DISTRIBUTIONS

The location/outflow-quantity distribution provides the amount of outflow at various locations along the potential interface with man's environment. In this example, the distribution is the outflow flux

Figure 3. The location/arrival-time distribution along the river for the pond leakage

Figure 4. The location/outflow-quantity distributions at the river

versus the location along the riverbank. The needed data are available from the flow kinematic results summarized in Table 1 and Figure 1. Use of these data will demonstrate the natural development of the location/outflow distributions and those steps involved in utilizing the arrival curves for the two-dimensional steady flow systems.

The example flow system in Figure 2 is conveniently considered in three parts depending upon the pertinent arrival location and the contaminant's route to the final outflow boundary: first, the arrival results at the river for all the fluid that bypasses both wells and moves directly to the river; second, the arrival results at the pumped well; and third, the final arrival at the river of the pumped water which is returned to the subsurface flow system by the injection well. Each of these parts will be considered separately and then combined to provide the final arrival results. Since consideration of the fluid bypassing the wells is simplest, it is discussed first.

POND LEAKAGE BYPASSING THE WELLS

For water coincident contaminants, the location/outflow distribution for the pond leakage bypassing the wells is obtained from the kinematic results of the hydrologic analysis from Table 1. In particular, the outflow location, s , from Column 5 is plotted against the boundary outflow flux (q from Column 6 of Table 1 divided by the scaling q_0 value). The resulting curve or location/outflow quantity distribution for the bypassing pond fluid is shown in Figure 4. Those parts in the figure representing the bypassing fluid are seen as the areas between pathlines 18 and 11-A-33 and pathlines 45-A-12 through 17 (see Figure 2 and footnote of Table 1). The remaining part of the curve in Figure 4 will be discussed after considering the arrival results for the pond leakage intercepted by the pumped well.

POND LEAKAGE ENTERING THE PUMPED WELL

Though a location/outflow distribution could be provided for the pumped well, it is easier to consider the pumped well in steady flow systems differently. In particular, the location involved with the location/outflow distribution is the angular position around the well casing and the outflow is the groundwater entering the well. The small distances around the well casings and small outflow variations in those distances suggest the desirability of (1) working with integrated or cumulative flow rates rather than point values, and (2) centering the emphasis on the quantity of fluid arrival at the well rather than concentrating upon the arrival location around the well casing, which is so small.

Both of the above suggestions are feasible and beneficial. The cumulative or integrated outflow rates are readily available since the kinematic stream function is precisely the cumulative flow rate. Also, associated with every arrival location is a corresponding arrival time, so the change to arrival quantities is appropriate and easily accomplished. The net result is the cumulative quantity/arrival-time curve or distribution which simply interrelates the cumulative outflow rate with the arrival times.

The quantity/arrival-time distribution for the pumped well in Figure 2 is the response at the well of an instantaneous fluid pulse leaving the pump at time, t_0 . From Figure 2 the pathlines along which fluid passes from the pond to the pumped well are numbered 23+ through 32 and also 1 and 2+. These are designated in Table 1 as pathlines 1, 2, 2-A-3, and 23-C-24 through 32. For these pathlines (i.e., streamlines in steady flow system) the cumulative flow rates or stream function values Q_i/Q_0 , from Column 4 in Table 1, are plotted in Figure 5 as the right ordinate versus the arrival times, $T - t_0$, from Column 2. As the data are plotted using the ordinate on the right, two curves are obtained; one very low, flat curve at the bottom (shaded) of Figure 5 and the upper horseshoe-shaped curve truncated by the ordinate $Q_i/Q_0 = 1$. The lower curve is conveniently transferred to a more useful location on the graph by adding 1.0 to each Q_i/Q_0 value for pathlines 1 through 2-A-3. In effect, adding 1.0 to the Q_i/Q_0 values simply continues the cumulative flux on to values greater than 1 rather than reverting or starting over at zero when pathline 1 in Figure 2 is crossed.

Figure 5. The quantity/arrival-time distribution for the pumped well as obtained from the integrated outflow rates

Theoretically, adding 1 is equivalent to proceeding to the next Riemann Sheet at the stream function branch cut represented by the steady path-line 1. Addition of 1.0 to the cumulative relative flux values gives the dashed continuation of the previous higher curve in Figure 3 and provides a single, complete horseshoe-shaped curve of the arrival results.

From the complete horseshoe-shaped curve the first arrival time of contaminated fluid at the pumped well is 8.84 years. The actual accumulative amount of contaminated water which has arrived up to that time is $Q/Q_0 = 0.0$ since it is the first fluid arrival. Slightly later, at 9.0 years after departure from the pond, the upper complete curve in Figure 5 has two bounding values of Q_1/Q_0 ; i.e., 0.826 and 0.970. The actual cumulative flow rate, Q/Q_0 , since the first fluid arrival, is the difference in the bounding values or, in other words, $Q/Q_0 = 0.144$ at an arrival time $(T - t_0) = 9$ years. The Q/Q_0 values of 0.0 and 0.144 are plotted using the left ordinate in Figure 5 against the arrival times of 8.84 and 9 years, respectively, to provide two points on the quantity/arrival-time curve for the pumped well. Other values of Q/Q_0 are obtained in a similar manner. At each time the difference in ordinates represented in Figure 5 by the distance labeled A becomes an ordinate Q/Q_0 value for the quantity/arrival-time curve for the pumped well. The maximum value of A is equal to $Q_1/Q_0 = 0.362$, which is the asymptotic value of the arrival curve. The resulting complete curve in Figure 5 is the quantity/arrival-time distribution or curve for the pumped well.

To demonstrate use of the quantity/arrival-time curve to obtain the contaminant outflow into the pumped well, the effects of contaminated fluid steadily leaving the reservoir for 0.85 years or 310 days and subsequently followed by uncontaminated water will be evaluated. The arrival curves at the pumped well from Figure 5 for the fluid departing from the pond at $t_0 = 0$ and $t_0 = 0.85$ years are shown in Figure 6. The two curves represent the first and last arrival of the contaminated pulse at the pumped well. The zone between the two curves represents all of the arrival curves with departure times, t_0 , between

0 and 0.85 years. In fact, the area between the curves in Figure 6 is all of the contaminated water pulse reaching the pumped well. At any time greater than 8.84 years, the difference in vertical ordinates between the two curves is the relative inflow rate to the well of contaminated fluid at that particular time. The differences between the two higher curves are plotted as the lower peaking curve in Figure 6. The lower peaking curve is the quantity of contaminated fluid inflow to the well as a function of time and is vital in determining contaminant concentrations of the water pumped from the well.

The concentration of the water pumped from the well is obtained directly from the arrival curves as follows. First, from the maximum asymptotic value $Q_I/Q_0 = 0.362$ in Figures 5 and 6, the flow rate intercepted by the well, Q_I , as a fraction of the total loss from the pond, Q_0 , is found; i.e., $Q_I/Q_0 = 0.362$. In other words, only 36.2 percent of the total pond leakage rate ($Q_0 = 471.2$ gal/min or $Q_I = 170.6$ gal/min) is intercepted by the pumped well. The contaminant concentration during the 0.85 years of release from the pond is constant, i.e., C_0 . Accordingly, the only change of concentration denoted by C in the water pumped from the well is the dilution due to differences in arrival times at the well; i.e., the lower peaking curve in Figure 6. The relative concentration, C/C_0 , leaving the pumped well is obtained by dividing each value of Q/Q_0 , taken from the lower peaking curve in Figure 6, by $Q_I/Q_0 = 0.362$. The results are plotted in Figure 7 as Q/Q_I on the left ordinate and C/C_0 on the right scale as a function of the arrival time, T_I . The right ordinate is labeled as the inflow concentration to the injection well since for this example the water from the pumped well is reinjected into the groundwater flow system. The departure times from the injection well and the associated concentrations shown in Figure 7 are also given in Table 3 for later use.

If the pumped water were to be used for domestic or related purposes rather than reinjected, Figure 7 would directly provide the

Figure 6. Use of the quantity/arrival-time curve to obtain the contaminated fluid inflow to the pumped well

Figure 7. Concentration and amount of contaminated fluid pumped from well and reinjected as a function of time

Table 3. Effective pond departure times and injection well concentrations for various departure times from the injection well

[1] Injection well departure time, T_0 , yr (see Fig. 7)	[2] Input concentration to injection well from Fig. 7 (C/C_0)	[3] Effective departure time from pond, $t_0 = T_0 - 8.84$, yr
8.84	0.000	0.00
8.85	0.207	0.01
8.90	0.320	0.06
8.95	0.392	0.11
9.00	0.448	0.16
9.10	0.539	0.26
9.20	0.613	0.36
9.30	0.669	0.46
9.40	0.718	0.56
9.50	0.760	0.66
9.60	0.801	0.76
9.65	0.815	0.81
9.70	0.635	0.86
9.75	0.552	0.91
9.80	0.497	0.96
9.85	0.442	1.01
9.90	0.401	1.06
10.00	0.337	1.16
10.25	0.227	1.41
10.50	0.144	1.66
10.75	0.091	1.91
11.00	0.061	2.16
11.50	0.022	2.66
12.00	0.0028	3.16

concentration of contaminant in the water as time passed. Comparison of the concentration shown in the figure with appropriate domestic, agricultural, or industrial water quality standards would indicate the environmental consequences or seriousness of the pond leakage as intercepted by the well. Figure 7 will be used in this example for further evaluation of the effects of reinjection on the final contaminant arrival at the river.

REINJECTED FLUID ARRIVAL AT RIVER

The location/outflow-quantity distribution for the reinjected fluid is shown in Figure 4. It involves the flow between pathlines 11-A-33 and 45-A-12 with the part of the curve simply being a plot of results from Column 5 against values from Column 6 in Table 2. Because of the time-dependent concentration to the injection well shown in Figure 7, special methods for using this part of the location/outflow curve are required.

This completes the steps necessary to obtain the location/arrival-time distributions for the three parts of the flow system. Note that the several subflow systems comprising the example just covered are in themselves representative of other situations. For instance, the pumped well part of the evaluation is typical of the analysis to determine the expected contaminant concentration entering any pumped well, whether for domestic, agricultural, municipal, or industrial use. Similarly, the techniques used in other parts of this example evaluation lend themselves to a wide range of applications.

USE OF THE LOCATION/ARRIVAL-TIME DISTRIBUTION

The example pond leakage case discussed earlier, where water coincident contaminants entered the ground for a period of 0.85 years, will illustrate use of the location/arrival results in Figure 3. The location/arrival curves for the first contaminant released at $t_0 = 0$ and for the last contaminated fluid leaving the pond at $t_0 = 0.85$ years are

plotted in Figure 8. With the exception of the river inflow from the injection well, all the other location arrival curves, if plotted, would lie between the $t_0 = 0$ and the $t_0 = 0.85$ curves. Thus, at any time, T , only locations lying between the two curves are exuding contaminated fluid into the river. For example, at $T = 17.5$ years from Figure 8, contaminant inflow to the river will occur only between $s = 325$ and 610 feet, 808 and 903 feet, 2335 and 2379 feet, and also between $s = 3995$ and 4150 feet. Similarly, at any other time, T , the location along the river where contaminants will enter is represented by the vertical distance between the $t_0 = 0$ and $t_0 = 0.85$ year curves. Between these two curves (shaded area) the contaminant concentration in the groundwater entering the river is unchanged or, in other words, is of the same concentration as departed from the pond. This absence of change in concentration while passing through the subsurface flow system is the consequence not only of considering just fluid coincident contaminants and of neglecting the very small effects of hydrodynamic dispersion, but also of the flow system and the concentration leaving the pond remaining steady during the 0.85-year release period. If the pond input concentration had changed with time as, for example, occurs with the injection well, then the output concentrations would have varied also.

The variation of the input concentration with time of the injected fluids directly affects the outflow concentration at the river from the injection well. Accordingly, the location/arrival-time distribution must be used differently for the injection well. In particular, the outflow to the river between pathlines 33 and 45 imposes additional changes on the outflow concentration, which are incorporated into the analysis with moderate ease.

The change of input concentration to the injection well is available from Figure 7 or Table 3. If several values of C/C_0 from Column 2 in Table 3 are selected and the associated effective departure times from the pond (t_0 values in Column 3) are used, then the location/arrival curve for each relative concentration, C/C_0 , value can be obtained and plotted as in Figure 8 by using the location/arrival-time distribution in Figure 3. In Figure 8, for the injection outflow region of

Figure 8. The consequences at the river of pond leakage

s greater than 2380 feet and less than 3990 feet, the resulting curves of outflow location at various times for the different concentrations are shown. Accordingly, the location of contaminants entering the river and the concentration at any time are readily available from the location/arrival results. With the concentration, time, and location results obtained as in Figure 8, the location/arrival-concentration results at the river can be determined.

THE LOCATION/ARRIVAL-CONCENTRATION DISTRIBUTION AT THE RIVER

The concentration of contaminants arriving at the river was found in the last section to vary with time along the river where the injected fluid emerges. These time variations are conveniently incorporated into the evaluation of environmental consequence through a location/arrival concentration curve. As the name implies, such a curve is

essentially the same as the location/outflow-quantity curve already described except the fluid outflow quantity is replaced by the contaminant concentration. The curve for the example flow system is shown in Figure 9 as obtained from the results in Tables 1, 2 and 3.

In Figure 9, the concentration C/C_0 is a constant value of 1.0 (the upper and lower rectangular areas in Figure 9) for all the locations along the riverbank except where the injected water emerges. For the outflow distances between pathline 33 and pathline 45 where the injected water emerges, the concentration changes with time; i.e., in Figure 8 for all times greater than 17.65 years, the concentration changes with the location s along the river bank where the injected fluid emerges. For example, at $T = 17.9$ years in Figure 8 the outflow for a concentration $C/C_0 = 0$ is at $s = 3000$ feet and $s = 3612$ feet and for $C/C_0 = 0.392$ the outflow is at $s = 3275$ feet and at $s = 3375$ feet, etc. These locations and concentrations lie on the curve labeled $T = 17.9$ years in Figure 9. The results in Figure 9 are, in fact, the same as in Figure 8 except the parameter is T in the former and C/C_0 in the latter.

With steady flow systems and non-time-dependent source concentrations, the location/arrival results of Figure 9 are very simple distributions of the outflow concentration variation along the riverbank at different times and need not be considered in great detail. However, as illustrated here, when the input concentration (as in the case of the injection well) varies with time, the location/arrival-concentration relationship is usually a complicated distribution and necessarily must be used as described in the following section.

USE OF THE LOCATION/ARRIVAL-CONCENTRATION AND LOCATION/OUTFLOW-QUANTITY DISTRIBUTIONS

The outflow rate of contamination is obtained by combining the arrival concentration and fluid outflow flux as functions of the outflow

Figure 9. The location/arrival-concentration distributions of contaminants entering the river

location along the riverbank. Specifically, the differential contaminant outflow rate, dW , through an incremental riverbank length, ds , is:

$$dW = C q ds \quad (13)$$

or expressed in the concentration and outflow flux:

$$dW = \frac{C}{C_0} \cdot \frac{q}{q_0} (C_0 q_0) ds \quad (14)$$

where C/C_0 is the concentration as in Figure 9, q/q_0 is the relative fluid discharge flux as in Figure 4, and $(C_0 q_0)$ is the conversion constant, being the product of the original pond concentration and the scaling outflow flux into the river.

The location/outflow-concentration distribution (Figure 9) and the location/outflow curve from Figure 4 are readily combined to provide the integrand of Eq. (14), $\left(\frac{C}{C_0} \cdot \frac{q}{q_0}\right)$, as a function of the outflow locations (Figure 10). In the figure, the effect of the gradually changing fluid outflow flux and the more rapidly varying relative concentrations is apparent. For those outflow locations not associated with the injection well, the contaminant outflow rate is the same for any time whereas with the injection well outflow, a different curve is associated with each outflow time selected.

The combined results in Figure 10 are simply another location/outflow-quantity distribution where now the outflow is the contamination outflow flux or quantity of the specific contaminant emerging into the river as a function of the outflow location. Therefore, the final results needed to obtain the amount of contamination outflow potentially to interface with the biosphere are obtained in the same ways as described previously in Paper I. The location/contamination-outflow quantity distributions in Figure 10 and the location/arrival-time distributions represented in Figure 8 are used together to provide the total contamination outflow as a function of time. Figure 10 gives the integrand in Eq. (14) whereas the limits for integration come from the location/arrival-time distribution in Figure 8. Upon integration, the

Figure 10. The location/contaminant-outflow quantity distribution into the river

Figure 11. The outflow rate of contamination into the river from the pond leakage

total inflow rate of contamination is obtained. For example, at $T = 15.5$ years, the contamination inflow rate, W_T is:

$$W_T = C_0 q_0 \int_{885 \text{ ft}}^{1965 \text{ ft}} \frac{C}{C_0} \cdot \frac{q}{q_0} ds = 6.77 \text{ lb/day} \quad (15)$$

At a later time, $T = 18$ years, the inflow rate W_T is:

$$W_T = 5.996 (10^{-3}) \left\{ \int_{250 \text{ ft}}^{390 \text{ ft}} \frac{C}{C_0} \cdot \frac{q}{q_0} ds + \int_{887 \text{ ft}}^{894 \text{ ft}} \frac{C}{C_0} \cdot \frac{q}{q_0} ds \right. \\ \left. + \int_{2390 \text{ ft}}^{2400 \text{ ft}} \frac{C}{C_0} \cdot \frac{q}{q_0} ds + \int_{2850 \text{ ft}}^{3625 \text{ ft}} \left(\frac{C}{C_0} \cdot \frac{q}{q_0} \right) ds + \int_{3995 \text{ ft}}^{4232 \text{ ft}} \frac{C}{C_0} \cdot \frac{q}{q_0} ds \right\} \quad (16)$$

or, upon evaluation,

$$W_T = 5.28 \text{ lb/day} \quad (17)$$

where the C_0 and q_0 values are from Figures 1 and 4 with the appropriate conversion of units to give W in the units of pounds per day of contaminant outflow into the river.

Through evaluating integrals similar to Eq. (15) and (16) for other times, the complete variation of outflow rates of contaminants with time is obtained as the lower irregular outflow curve shown in Figure 11.

The higher, dashed curve in the same figure is the outflow to the river when no pumping or injection well was used (see Figure 5 in Paper I).

The reduction in peak outflow rates of contaminants into the river by pumping suggests the usefulness of arrival distributions in evaluating the benefits of different groundwater management possibilities.

The inflow rate of contaminants into the river in Figure 11 is the second of the two final results needed to completely evaluate the environmental consequences of, in this case, the pond leakage. It shows in easily usable form how much contaminant will enter the river with passing time, and knowing the expected amount of contaminants at various times, application of appropriate domestic, agricultural, or industrial water quality standards will indicate the environmental consequences of the subsurface pollution problem. In retrospect, the results in Figure 11 were obtained through judicious use of the location/arrival distributions for the various parts of the complicated flow pattern.

FINAL RESULTS FOR EVALUATING ENVIRONMENTAL CONSEQUENCES

The complete environmental impact is easily provided by Figures 8 and 11. For instance, from Figure 11 at $T = 15.87$ years after the first contaminant release, the peak outflow quantity or rate, W , is 8.05 pounds per day from the dashed curve. This outflow rate is the total contaminant outflow entering the river at $T = 15.87$ years and from Figure 8 it all enters the river between $s = 930$ feet and $s = 2150$ feet. The concentration entering the river between these two points is from the shaded area $C = C_0$.

At any other time, the same final results can be obtained from using Figures 8 and 11. In each instance, the total inflow rate of the particular water coincident contaminant is given irregular curve in Figure 11. The location/arrival curves directly provide the location along the river where the contaminant inflow will occur and also provides the inflow concentration.

CONCLUSIONS

By combined application of location/arrival-time and location/outflow-quantity distributions, the complete results needed to determine the environmental consequences of subsurface pollution can be presented. This method provides quantitative results for how much contaminant would interface with the biosphere, the location where that amount may first contact man's environment, and the time when the subsurface flow system will no longer isolate the contaminant. Certainly, these are the facts needed by the decision-maker to choose alternatives and allow, disallow, or require corrective action based upon the environmental consequences. Thus, the summary results shown in Figures 8 and 11 provide the primary information necessary to evaluate the environmental consequences of the subsurface pollution problem.

The next two papers in this sequence will provide methods to consider heterogeneous permeable systems with irregular flow geometry and transient flow systems in two dimensions. As arrival distributions for these more complicated systems are developed, a broader class of hydrologic systems can be treated.

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NOTATIONS

		<u>Units</u>
D_o	stratum or slab thickness	L
C	contaminant concentration pumped from the well and reinjected	F/L^3
C_o	contaminant concentration in the pond	F/L^3
$\frac{C}{C_o}$	concentration of contaminants in the water	none
$\frac{C}{C_o} \frac{q}{q_o}$	outflow flux of contaminant to the river	none
H_o	head in the pond	L
$H' = 1$	transient head in pond (equals 1 for steady flow)	none
j	summation index taking on values of 1 and 2, here	none
K_o	hydraulic conductivity of the material	$(L^3/T)/(L^2L/L)$
$m_1=Q_1/(D_oK_o)$	strength of the pumped well (sink)	L
$m_2=Q_2/(K_oD_o)$	strength of the injection well (source)	L
$N = 2$	since both a point source (pumped well) and sink is involved	none
P	effective porosity	none
Q	cumulative flow rate of contaminated fluid with $Q = 0$ corresponding with the first contaminant arrival at an outflow boundary	L^3/T
Q_I	flow rate intercepted by the pumped well and reinjected at the injection well	L^3/T
Q_i	cumulative flow rate of contaminated fluid (see Eq. 8)	L^3/T
Q_o	steady fluid outflow rate from the pond	L^3/T

		<u>Units</u>
$\frac{Q_I}{Q_0} = 0.362$	fraction of the pond leakage intercepted by the pumped well	none
Q_1	pump discharge rate of the well (always negative)	L^3/T
Q_2	injection flow rate into the well (always positive)	L^3/T
q	boundary groundwater emission or outflow flux per unit distance along the river	$(L^3/T)/L$
q_0	a convenient constant value of q used for scaling	$(L^3/T)/L$
R	large radial distance to the remote outer boundary	L
r_0	radius of the cylindrical pond	L
s	location where the contamination reaches the river boundary (see Eq. 11).	L
T	arrival time at an outflow boundary	T
T_I	injection time at the well	T
T_i	arrival time at the pumped well	T
T_o	departure time of fluid from the injection well	T
t	time	T
t_o	departure time from the pond	T
U	gradient strength of the uniform lateral flow	L/L
$\underline{v}$	pore velocity vector	L/T
W	outflow rate of a specific contaminant entering the river	F/T
X	distance along the x-coordinate direc- tion to the river	L
x and y	Cartesian coordinates	L

		<u>Units</u>
x_0	x-coordinate of a starting point on the pond wall	L
x_1	x-coordinate of the center of the pumped well	L
x_2	x-coordinate of the center of the injection well	L
y_0	y-coordinate of a starting point on the pond wall	L
y_1	y-coordinate of the center of the pumped well	L
y_2	y-coordinate of the center of the injection well	L
ϕ	groundwater potential	FL/F
∇	gradient operator	1/L
ϵ	approximation error in head at the pond introduced by wells	L
ϵ'	approximation error in head at remote boundary introduced by wells	L

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EVALUATING THE ENVIRONMENTAL CONSEQUENCES
OF GROUNDWATER CONTAMINATION

III. Obtaining Contaminant Arrival Distributions for
Steady Flow in Heterogeneous Systems

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ABSTRACT

The versatility of the new contaminant arrival distributions for determining environmental consequences of subsurface pollution problems is demonstrated through application to a field example involving land drainage in heterogeneous porous materials. Though the four phases of the hydrologic evaluations are complicated because of the material heterogeneity encountered in the field problem, the arrival distributions still effectively summarize the minimal amount of data required to determine the environmental implications. These arrival distributions yield a single graph or tabular set of data giving the consequences of the subsurface pollution problems. Accordingly, public control authorities would be well advised to request that the results of subsurface pollution investigations be provided in the form of arrival distributions and the resulting simpler summary curve or tabulation. Such an objective is most easily accomplished through compliance with the requirements presented in Paper I for assuring a complete subsurface evaluation.

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INTRODUCTION

The previous papers in this sequence presented the new location/arrival-time and location/outflow-quantity distributions as simple, effective tools for evaluating subsurface pollution. 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 the contaminant transport analysis. Once these phases are completed, the results are effectively summarized and easily used through the arrival distributions.

This paper further elaborates on the technical basis of arrival distributions with particular emphasis on their use in field situations involving heterogeneous porous materials. The example used to illustrate these techniques, though restricted to steady two-dimensional flow, considers the environmental implications of contaminant movement into subsurface drains under conditions of complicated flow geometry and heterogeneous materials.

The four evaluation phases comprising the hydrologic analysis for the field example are stated first and those special features needed for heterogeneous systems are illustrated. The hydrologic evaluation results are then used to satisfy the general requirement (Paper I) necessary to assure a complete and sound evaluation of the environmental consequences. Fundamental to the general requirements are the contaminant arrival distributions. Accordingly, those steps necessary to obtain the contaminated fluid location/arrival-time and the location/outflow-quantity distributions from the hydrologic analysis are then described for the subsurface drainage system. Together, these arrival results are used to determine the environmental implications. These final results show the amount and concentration of contaminants emerging with time at the location of first direct interface with man's environment.

THE TECHNICAL BASIS FOR ARRIVAL DISTRIBUTIONS

The contaminant arrival distributions originate with and depend directly upon the measurement and evaluation capabilities of subsurface hydrology and geochemistry. This is essentially axiomatic since arrival distributions simply provide efficient tools to summarize the final hydrologic results needed for the environmental evaluation. These extensive subsurface hydrologic results come from a four-step evaluation sequence described in the previous paper:

- System identification
- New potential determination
- Flow system kinematics
- Contaminant transport analysis

System identification involves determining and measuring those physical and chemical characteristics pertinent to evaluating the subsurface contaminant movement. The new potential determination phase involves those methods used in determining 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 dispersive effects and the retarding effects of exchange or other geochemical reactions between individual constituents and the porous material.

Together, these evaluation phases provide the technical basis for the contaminant arrival distributions. This paper will emphasize methods that will explore and clarify means of evaluating heterogeneous systems and using such results through the arrival distributions.

ARRIVAL DISTRIBUTIONS FOR FLOW IN HETEROGENEOUS SYSTEMS

Many of the same methods already described and illustrated for steady, two-dimensional flow situations are used to obtain arrival distributions in heterogeneous systems. Additional considerations center on a more comprehensive system identification phase and, generally, more complicated evaluations are needed in the three subsequent phases. The emphasis here is on the additional identification requirements and more complex approaches required for incorporating the effects of heterogeneous materials. These additional methods are best described and illustrated by an example.

SYSTEM IDENTIFICATION FOR THE EXAMPLE EVALUATION

The example system is part of a drainage study conducted near Grandview, Idaho, which is ideal for illustrating the use of arrival methods in heterogeneous systems. Accurate field data are available and the system is essentially a lateral two-dimensional flow system, which greatly simplifies the discussion and graphical display of results.

The study involved designing a drainage system for land between the Grandview Irrigation Company canal and the Snake River, with the whole project located about 3 miles west of Grandview, Idaho. More details of this area including the canal, roads, and locations where the field measurements were made are shown in Figure 1. The measurement locations shown in the figure, denoted by open circles, are piezometer banks used to measure groundwater potential. The hydraulic conductivity measurements are also shown along the dashed line near 20+00 and along the county road.

Hydraulic conductivity was measured using the Kirkham Piezometer Method (Kirkham, 1945). Five replicated measurements were made at each of the open circles along the dashed line, for example, at A-20+00, B-20+00, C-20+00, etc. At intermediate points, such as A-B-20+00 or B-C-20+00, three replicated measurements were made. These measurements provided the hydraulic conductivity variation along the dashed line in Figure 1.

Figure 1. Field measurement locations for groundwater potential and hydraulic conductivity in the Grandview Drainage Study

Groundwater potential was measured by installing piezometer clusters or banks at the locations shown by the small open circles in Figure 1. During piezometer installation, the penetrated soil material and the depth of the much less permeable bottom layer were observed and recorded to better define the subsurface system. Every installed cluster contained from two to five individual piezometers with each terminating at a different depth to measure any vertical variations in potential. Following installation and periodically during the year the piezometers were flushed to assure accurate water level measurements. The resulting measurements provided very good groundwater potential data over the entire area with essentially no observable vertical differences in potential. This lack of significant difference in vertical potential indicated that a two-dimensional analysis would be satisfactory. This conclusion was further supported by the generally shallow system (20-25 ft. thick) of soil of wind-blown origin and the negligible stratification observed during piezometer installation.

The energy dissipation method of determining hydraulic conductivity is ideally suited for use in this example. The general theory for transient flow systems (Nelson, 1969) requires the field data already described, namely the potential distribution over the region of interest for at least one time, and the hydraulic conductivity, in this case along the one line. With these data the hydraulic conductivity distribution over the entire problem area can be provided by one of several numerical schemes. In this example, a combined approach of potential data fitting, numerical generation of instantaneous streamlines, and quadrature evaluation of the dissipation integral was used. The steps involved for this specific application are described in detail by Nelson (1968). The stated restriction to steady flow in the referenced paper was demonstrated unnecessary when the more general theory was later derived (Nelson, 1969). Two results from that earlier description are included here as Figures 2 and 3.

Figure 2 shows the fitted groundwater potential data for November 20. The measured potential is represented as equipotential lines that vary

Figure 2. Equipotential and instantaneous streamline distribution for November 20, Grandview Drainage Study

Figure 3. Hydraulic conductivity (ft/yr) distribution obtained by energy dissipation method, Grandview Drainage Study

from 2365 to 2388 feet of water above sea level in the region of original data. Also shown is the potential in an extended region, where the best available estimate of potential between the measured region and the Snake River was used. This extended region is required to reach the realistic river boundary for the drainage systems. Over the entire area in Figure 2, instantaneous streamlines for November 20 are shown as the longitudinal lines, thereby completing a utilitarian flow net for this heterogeneous two-dimensional region.

Figure 3 gives the hydraulic conductivity distribution in units of feet per year as contours of equal conductances for the entire region. The instantaneous streamlines along which the dissipation integral was evaluated to obtain the hydraulic conductivities are again included in the figure. Although the fitting procedure is the one illustrated here, there are other useful approaches, all originating in the basic theory but varying in complexity. Some of these are simple and easily accomplished but are more approximate; others involve more effort but are more accurate. Such flexibility is essential in meeting the practical situations encountered in actual field problems. For example, in the earlier stages of an investigation, when field data are scarce and often of poorer quality, the more approximate techniques save time and effort.

The effective porosity distribution over the region is the last major result needed to complete the system identification phase. Sufficient field chemical data or particular tracer results are not available on the Grandview study area to apply a regional inplace method of obtaining the spatial variation of effective porosity. Further, for this area, the time required to get a long enough record could well make gathering of such chemical data impractical. However, on the positive side, the porous material is more uniform than usual as a result of being wind deposited, and the hydraulic conductivity distribution shows less variation in conductance than in many field situations. Some laboratory results provided values ranging from 0.18 to 0.23. Based upon the moderate uniformity and limited range of porosities measured, it was decided to use a uniform value of 0.2 over the study area.

This completes the system identification aspects of the evaluation for essentially water coincident contaminants. If exchange or geochemical reactions were involved, the exchange and reaction rate characteristics would also have to be determined as part of the identification process. Once the system characteristics are obtained, they are used to determine new potential distributions.

NEW POTENTIAL DETERMINATION FOR THE EXAMPLE SYSTEM

Determining the new potential distribution after drains are installed is more involved with variable conductivity and irregular field boundary conditions than are the more idealized problems. Accordingly, a finite difference solution code for steady systems, STEADY (Nelson, 1962; Reisenauer, 1963), was used to provide this new distribution.

A square grid of 150 feet on a side was first placed over the entire area. Hydraulic conductivity values at each grid point were used from the identification results in Figure 3. The location of the proposed tile drainage system was represented by the appropriate grid points, and the groundwater potential at each grid point representing the drains was also specified to represent the water level at that particular point, as shown in Figure 4. The other boundary conditions for the saturated flow problem were the water levels beneath the canal on the left hand or upper end of the figure and the water level in the Snake River on the other, lower end. The remaining side boundaries in Figure 4 were maintained as streamlines; therefore, no flow occurred normal to these boundaries.

The STEADY computer code provided an approximate solution at each of the remaining grid points inside the region for the new groundwater potential expected after the drains are in place. The numerical values of the new potential at the grid points were contoured to obtain the equipotential map in Figure 5 by using the SURFACE II code from the Kansas Geological Survey (Sampson, 1973). With the new potential distribution determined, and using the hydraulic conductivity distribution, the flow system kinematics are next obtained.

Figure 4. Finite difference grid and boundary conditions used to determine new potential distribution after drainage

Figure 5. New potential distribution and flow pathlines expected after drain installation

FLOW SYSTEM KINEMATICS FOR THE EXAMPLE

The flow system kinematics are also more complicated to determine in heterogeneous field situations. Fortunately however, a range of methods can accomplish the required evaluations, depending on the trade-off selected between the analysis costs and the degree of approximations used. Rather than use the more precise but involved methods similar to those already applied in the hydraulic conductivity distribution, the less involved, approximate approach will be illustrated here. This approach is particularly well-suited for steady, two-dimensional flow systems as in the Grandview example. The approximate kinematics approach uses the utilitarian flow net shown in Figure 5 to determine flow paths, travel times along those flow paths, outflow fluxes to the drains, and the location along the drains where the contaminants enter.

The utilitarian flow net in Figure 5 is first converted to numerical data through use of a mechanical, or sonic, digitizer using the small interactive computer code DIGIT1. This code enables digitizing of the flow net, streamline by streamline, and stores the coordinates of equipotentials along the streamlines in appropriate files for subsequent use. Next, the interactive code FLOW2W uses the digitized file data, porosity, and the previously generated hydraulic conductivity, to determine the travel times along individual streamlines. The code also provides plots of the results as isochronal contour lines by automatically calling and utilizing SURFACE II (Sampson, 1973). Figure 6 is the isochronal map resulting from the approximate kinematic analysis for one of the drains, i.e., the South Drain F-G-H.

In Figure 6, the present location of the contaminated fluid front is shown as the isochronal line $t = 0$. The numerous pathlines numbered 1 through 36 indicate the flow paths which individual fluid particles will follow from their starting locations at $t = 0$ to the drain. The greater variations in hydraulic conductivity, gradient, and flow path length combine to provide more irregular results in heterogeneous systems, as is apparent in Figure 6. The much longer times associated with groundwater pollution problems as compared to surface water or air pollution

problems are also dramatically emphasized by the travel times for this actual field problem.

Figure 6. Present contaminated fluid front and expected movement along pathlines toward Drain F-G-H

Those parts of the kinematic results in Figure 6 needed for the arrival data at the drain are summarized in Table 1 for subsequent use. With this summary, three of the four overall hydrologic evaluation phases have been completed for the example heterogeneous system. Since dispersion is not included and only conservative contaminants such as chlorides or sulphates are considered, the transport analysis is not required. Accordingly, all of the results from the rather extensive geologic investigations and several hydrologic evaluations needed to obtain the arrival distributions are available in Table 1. With the aid of these distributions, the environmental consequences are quickly and easily evaluated.

Table 1. Summary of expected contaminant arrival results at Drain F-G-H from hydrologic evaluations of area near Grandview, Idaho

[1] Pathline designation (see Fig. 6)	[2] Travel time along path- line, $T-t_0$, yr	[3] Arrival loca- tion along drain, s, ft	[4] Unit outflow rate, q, gal/hr/ft of drain	[5] Cumulative relative flow rate, Q_i/Q_0
1	342.1	0	0.060	0.00000
2	323.5	130	0.064	0.00381
3	295.6	245	0.071	0.00748
4	272.1	320	0.077	0.0101
5	228.8	397	0.094	0.0132
6	126.3	560	0.150	0.0236
7	100.4	688	0.212	0.0336
8	77.7	820	0.581	0.0583
9	59.8	939	0.937	0.1022
10	50.7	1010	0.998	0.1347
11	38.2	1107	1.062	0.1819
12	39.3	1175	1.136	0.2173
13	50.0	1262	1.261	0.2666
14	61.1	1335	1.320	0.3112
15	64.8	1420	1.390	0.3656
16	61.1	1502	1.630	0.4219
17	52.2	1600	1.670	0.4993
18	52.8	1665	1.660	0.5504
19	66.7	1728	1.640	0.5996
20	63.3	1790	1.610	0.6473
21	68.1	1870	1.545	0.7069
22	69.3	1934	1.453	0.7523
23	67.7	2000	1.050	0.7920
24	76.4	2054	0.885	0.8164
25	104.1	2149	0.724	0.8526
26	101.2	2180	0.681	0.8628
27	91.9	2215	0.642	0.8738
28	88.1	2230	0.628	0.8783
29	78.9	2298	0.570	0.8976
30	73.4	2355	0.525	0.9124
31	73.1	2450	0.458	0.9345
32	102.2	2585	0.334	0.9597
33	79.0	2740	0.197	0.9792
34	73.8	2810	0.172	0.9853
35	74.2	2907	0.128	0.9922
36	76.3	2980	0.083	0.9958

EVALUATING ENVIRONMENTAL CONSEQUENCES FOR THE EXAMPLE PROBLEM

The environmental consequences of water coincident contaminants reaching Drain F-G-H (see Figures 4, 5 and 6 for the specifics of location, configuration, etc. for Drain F-G-H) are evaluated by satisfying the five unified requirements described in Paper I; specifically, these are to:

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.
3. Provide the contaminated fluid location/outflow-quantity distribution for each outflow boundary in item 1.
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.
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 requirements 2, 3 and 4.

LOCATION OF POTENTIAL INTERFACE WITH MAN'S ENVIRONMENT

The potential interface of contaminated groundwater with man's environment is more apparent in the drainage example than in many other applications. The first point of possible direct contact with man is at the drain outfall (point F in Figure 6), though the groundwater outflow boundary is along the entire length of the tile drain. The buried drain intercepts and effectively isolates the contaminated fluid for the very short time of conveying it to the drain outfall. To obtain the expected

consequences at the outfall or first point of potential interface, the arrival distributions along the outflow surface are used as outlined by the general evaluation requirements.

THE LOCATION/ARRIVAL-TIME DISTRIBUTION

The location/arrival-time distribution provides the location along the drain where the contaminated fluid will arrive as time passes. In a sense, this distribution is a summary of all the subsurface flow effects and is a complete arrival response along the drain. The outflow location is the distance, s , along the drain starting at the drain outfall (point F in Figure 6) and continuing toward the head end of the tile line. That location, s , is plotted against the elapsed arrival time, $(T-t_0)$, from Table 1 to provide graphically the location/arrival-time curve along the drain. The resulting curve is shown in Figure 7. The curve is more irregular than in previous examples considered in these papers because of the heterogeneities and the more complicated flow pattern that may occur in natural systems. Though the shape of the curve is more irregular, the overall simplicity of the location/arrival-time distribution and its completeness in summarizing results of the hydrologic evaluations are evident. Figure 7 or the results in Columns 2 and 3 in Table 1 satisfy the second general requirement to assure adequate evaluation of the environmental consequence of the subsurface contaminants entering the drain. The third requirement is satisfied in the next section for the example drainage problem.

THE LOCATION/OUTFLOW-QUANTITY DISTRIBUTION

The location/outflow-quantity distribution provides the amount of fluid outflow per unit length into the drain. The needed data to provide such a curve for the fluid coincident contaminants are available from the flow kinematic results in Table 1. In particular, the location, s , along the drain and the unit outflow flux, q , are plotted to give the distribution shown in Figure 8.

Although the location/outflow rate curve in the figure is irregular because of system heterogeneities, it effectively summarizes the second vital part of the data that must come from many hydrologic analyses to evaluate the environmental implications.

Figure 7. The location/arrival-time distribution of contamination along Drain F-G-H

Figure 8. The location/quantity-outflow distribution of contamination along Drain F-G-H

CHEMICAL ARRIVAL DISTRIBUTIONS

The chemical arrival distributions are of minor importance for this particular problem because (1) only water coincident contaminants are considered, (2) the flow system is steady, and (3) the input concentrations are independent of time, largely because of limited field water quality data for the present condition. More extensive and detailed chemical analyses may have shown a variation in the concentration with the location along the present contamination front, i.e., along the $t = 0$ isochronal line in Figure 6.

If concentration varied with location along the contamination front, the situation could be handled similarly to that illustrated in Paper II. The varying concentration along the present front could be transferred to an arrival location, s , along the drain using the pathlines in Figure 6 and the results from Table 1. A location/arrival-concentration distribution, i.e., a plot of the arrival location along the drain and the concentration entering the drain, could then be obtained. Such a distribution is similar to Figure 10 in Paper II and would be used in the same way described there. Since no such measured variation in concentration along the present front is available, the location/arrival-concentration distribution is of very little significance. In fact, the relative concentration is independent of both time and space or is constant. That is:

$$\frac{C}{C_0} = 1.0 \quad (1)$$

and can be used in the sections to follow as required.

Results have now been provided that satisfy four of the five general requirements to assure careful and complete consideration of the environmental consequences of the subsurface pollution problem, in this case, the Grandview Drain F-G-H. These are simple in concept and can be easily used to satisfy the fifth and last requirement necessary to evaluate the environmental consequences.

USE OF THE DRAIN ARRIVAL DISTRIBUTIONS TO EVALUATE THE ENVIRONMENTAL CONSEQUENCES

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

$$W_T = C_0 q_0 \int_{s_1}^{s_2} \frac{C}{C_0} \cdot \frac{q}{q_0} ds \quad (2)$$

and further simplification results by substituting Eq. (1) in (2) to obtain:

$$W_T = C_0 q_0 \int_{s_1}^{s_2} \frac{q}{q_0} ds \quad (3)$$

At a particular arrival time, T , the location/arrival-time distribution (Fig. 7) provides the limits of integration, s_1 and s_2 , while the location/arrival-outflow distribution (Fig. 8) provides the integrand, q/q_0 , as a function of s . For example, since the first contaminant arrival is of interest, then $t_0 = 0$, and if the outflow rate at $T = 60$ years is desired, then:

$$W_{T=60 \text{ yr}} = C_0 q_0 \left\{ \int_{935 \text{ ft}}^{1320 \text{ ft}} \frac{q}{q_0} ds + \int_{1515 \text{ ft}}^{1747 \text{ ft}} \frac{q}{q_0} ds \right\} \quad (4)$$

where the lower and upper limits are the beginning and ending locations respectively of contaminated fluid inflow to the drain, as provided by the location/arrival curve at $T = 60$ years shown in Figure 7.

If the present contaminant constituent concentration were $C_0 = 8.33 \times 10^{-4}$ lb/gal and the results in Figure 8 or in Table 1 were used to evaluate the integrals in Eq. (4), then:

$$W_T = 60 \text{ yr} = 0.614 \text{ lb/day.} \quad (5)$$

As a second illustration, consider the outflow rate at $T = 100$ years. Then:

$$W_T = 8.33 (10^{-4}) \left\{ \int_{690 \text{ ft}}^{2100 \text{ ft}} \frac{q}{q_0} ds + \int_{2185 \text{ ft}}^{2568 \text{ ft}} \frac{q}{q_0} ds + \int_{2672 \text{ ft}}^{3090 \text{ ft}} \frac{q}{q_0} ds \right\} \quad (6)$$

or upon evaluating:

$$W_T = 1.626 \text{ lb/day.} \quad (7)$$

Similarly, additional times, T , could be chosen and the appropriate integrals evaluated to provide a complete distribution of the quantity of contaminant entering the drain as a function of time. The results of many such evaluations are shown in Figure 9 and give the variation of the outflow rate, W , with time, T .

There is an alternative, somewhat easier, approach to obtain the results in Figure 9 in cases like this where the flow system and concentration are both steady and independent of time. Under these conditions, it is convenient to evaluate only the flow rate part of Eq. (3) to obtain the cumulative flux rate, Q_i/Q_0 , i.e.,

$$\frac{Q_i}{Q_0} = \frac{1}{35.24} \int_0^s \frac{q}{q_0} ds \quad (8)$$

where $Q_0 = 35.24$ gal/min is the total steady outflow rate of water from the drain and q/q_0 is defined by the location/quantity-outflow distribution in Table 1 as shown in Figure 8. The cumulative flux in Eq. (8) is recognized as simply the classical stream function flux for the point s on the drain divided by Q_0 , the total flux entering the drain. The

Figure 9. The amount and concentration of contaminants that will interface with man's environment at the outfall of Drain F-G-H

relative flux, Q_1/Q_0 , defined by Eq. (8) is graphically presented in Figure 8 as the area to the left of the curve up to the particular locations along the drain, divided by the entire area to the left of the location/outflow-quantity curve.

The cumulative flux to various locations along the drain are evaluated using Eq. (8) and are tabulated in the last column in Table 1. With the flux values tabulated, a quantity/arrival-time curve of the type explained in detail and shown as Figure 5 in Paper II is obtained. The resulting curve is shown here as the curve in Figure 9 with the right-hand ordinate Q , the outflow rate of contaminated water. Also shown as a right ordinate is the concentration in the water at the drain outfall. Finally, direct comparison of Eq. (3) and (8), based on the procedure for deriving the quantity/arrival-time curve shows that Eq. (3) for the actual contaminant outflow rate W is, at most, within a constant multiplier of the quantity/arrival flux Q . Accordingly, the expected contaminant outflow rate, the outflow rate of contaminated water, and

the relative concentration of the contaminant as they vary with time are all shown in Figure 9.

FINAL RESULTS FOR EVALUATING THE ENVIRONMENTAL CONSEQUENCES OF DRAIN F-G-H

The environmental consequences at the drain outfall are easily available for any time from Figure 9. For instance, no contaminant is expected to interface with man during the first 37.77 years. At 50 years, 0.256 lb/day of contaminant is the expected outflow rate. The concentration $C/C_0 = 0.142$ at 50 years, with a present or initial concentration, $C_0 = 8.33 \times 10^{-4}$ lb/gal, gives an outflow concentration of 1.18×10^{-4} lb/gal.

Likewise, at any other time of interest, the total outflow rate of contaminant and concentration may be easily obtained from Figure 9. In each instance, the contaminant outflow rate in pounds per day is available from the left ordinate and the relative concentration from the right ordinate. Comparison of the concentrations and outflow quantities from the figure with appropriate domestic, agricultural, or industrial water quality standards would indicate the environmental consequences, or the seriousness, of the drain discharge to the environment.

CONCLUSIONS

By combined application of the location/arrival-time and location/outflow-quantity distributions, the complete results needed to determine the consequences of subsurface pollution can be presented as one simple figure. The simplicity of the summary results is maintained even when the hydrologic analysis is complicated by the effects of heterogeneous materials. Once the arrival results are obtained from the more complicated hydrologic analysis, the environmental consequences are available in simple and direct form. These summary results are the facts needed by public decision-makers to choose alternatives and allow, disallow, or

require corrective actions based upon the environmental consequences. Thus, the results shown in Figure 9 provide the most important information necessary to evaluate the environmental impact of the subsurface pollution problem. Accordingly, the public control authorities would be well advised to request, or even require, that the results of subsurface pollution investigations be provided in the form of arrival distributions and the resulting simpler summary figure or tabulation. Such an objective would be accomplished most easily by compliance with the five requirements for assuring a complete subsurface evaluation. The next paper in this sequence will provide methods to consider transient flow systems in homogeneous materials but with irregular flow geometry. Though many hydrologic and geochemical systems may be more complicated than those considered in our examples, these cases sufficiently illustrate those methods needed to develop arrival distributions from the more complicated hydrologic and geochemical systems.

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EVALUATING THE ENVIRONMENTAL CONSEQUENCES
OF GROUNDWATER CONTAMINATION

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

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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

$$\begin{aligned} H' &= 1 \\ N &= 1 \\ j &= 1 \end{aligned} \quad (1)$$

and

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

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 ft³/yr. The injection inflow rate rises to 2.6×10^7 ft³/yr at 1.5 years and then gradually diminishes toward the initial injection rate of 1.0×10^6 ft³/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) = $+1.0(10^6)$ ft³/yr
12. Q_M (maximum injection rate to well) = $+2.6(10^7)$ ft³/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

$$x(t_0) = x_{0,1} \quad (3)$$

and

$$y(t_0) = y_{0,1} \quad (4)$$

with

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

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 Runge 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 not 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 design- nation	Departure time, t_0 , 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.,

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

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 $\left(\frac{C}{C_0} \cdot \frac{q}{q_0} \right)$, as a function of the location s . For example, at $T = 8.5$ years, the contaminant outflow rate W to the river is

$$W_T = 8.33(10^{-5}) \int_{2240 \text{ ft}}^{2835 \text{ ft}} \frac{C}{C_0} \cdot \frac{q}{q_0} \Big|_{T = 8.5 \text{ yr}} ds \quad (7)$$

where the limits in Eq. (7) are the maximum location intercepts from Figure 4 or Figure 7, and the constant $C_0 q_0$ was evaluated using item 14 in Figure 1 and the q_0 value from Figure 5. Evaluation of the integral gives

$$W_T = 8.5 \text{ yr} = 0.0147 \text{ lb/min} = 0.882 \text{ lb/hr} \quad (8)$$

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

$$W_T = 8.33(10^{-5}) \int_{1435 \text{ ft}}^{3650 \text{ ft}} \frac{C}{C_0} \cdot \frac{q}{q_0} \Big|_{T = 10 \text{ yr}} ds \quad (9)$$

or

$$W_T = 10 \text{ yr} = 0.1305 \text{ lb/min} = 7.83 \text{ lb/hr} \quad (10)$$

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

	Outflow rates to the river		
[1] Time since first contaminant entered injection well, T, yr	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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