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A PROPOSED STRATEGY FOR ASSESSING COMPLIANCE WITH THE RCRA GROUND-WATER MONITORING REGULATIONS

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ABSTRACT: To satisfy the Resource Conservation and Recovery Act (RCRA) ground-water monitoring regulations, a hazardous waste management facility must have a ground-water monitoring system consisting of at least one upgradient and three downgradient wells and show that the downgradient wells are capable of immediately detecting a statistically significant amount of contamination at the water table. Because the regulations are subjective, it is often difficult for the owner/operator and the regulator to assess whether a monitor-well network satisfies the regulations. A probabilistic strategy is presented which satisfies the regulations and attempts to minimize subjectivity in evaluating the performance of a monitor-well network.

The proposed strategy is based on a determination of the likely ground-water flow paths through both the unsaturated and saturated zones and ground-water travel times. The approach involves three stages of analysis: 1) optimization of monitor well location, 2) evaluation of the sampling interval, and 3) assessing the monitor-well network performance through time.

KEYWORDS: ground-water monitoring, monitor-well network, RCRA regulations, quantification, strategy

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1. INTRODUCTION

Current RCRA ground-water monitoring regulations are subjective, making it difficult for the owner/operator and the regulators to resolve differences as to whether a monitor-well network satisfies the regulatory requirements. Sandia National Laboratories (SNL) has developed a probabilistic approach to meeting the RCRA regulations which attempts to minimize the subjectivity in evaluating the performance of a monitor-well network by prior agreement to a set approach and by defining and quantifying the performance measures to evaluate the monitor-well network.

This strategy was developed to determine the adequacy of an existing monitor-well network at a specific SNL waste site located in Albuquerque, New Mexico. The intent was to provide a mechanism which allowed the regulators and SNL to assess whether the number and locations of existing wells met the regulations. Quantification of the well-network problem also required clarification of regulatory requirements and definitions. A discussion of these requirements and definitions along with the proposed strategy for assessing compliance with the RCRA ground-water monitoring regulations is presented below.

2. REGULATORY REQUIREMENTS AND DEFINITIONS

To satisfy the RCRA ground-water monitoring criteria (40 CFR 265.91), "a ground-water monitoring system must be capable of yielding ground-water samples for analysis and must consist of: 1) Monitor wells (at least one) installed hydraulically upgradient (i.e., in the direction of increasing static head) from the limit of the waste management area. Their number, locations, and depths must be sufficient to yield ground-water samples that are: i) representative of background water quality in the uppermost aquifer near the facility; and ii) not affected by the facility; and 2) Monitoring wells (at least three) installed hydraulically downgradient (i.e., in the direction of decreasing static head) at the limit of the waste management area. Their number, locations, and depths must ensure that they immediately detect any statistically significant amounts of hazardous waste constituents that migrate from the waste management area to the uppermost aquifer." Additionally, the RCRA closure permit regulations (40 CFR 270.14c) require the "identification of the uppermost aquifer and aquifers hydraulically interconnected beneath the facility property, including ground-water flow direction and rate, and the basis for such identification (i.e., the information obtained from hydrogeologic investigations of the facility area)."

These regulations contain several terms which need to be defined prior to developing a strategy for assessing compliance. Also, the EPA regulations do not account for many of the hydrologic complexities associated with the arid southwest. In the southwest, it is not uncommon to find waste sites located hundreds of meters above unconfined alluvial aquifers (> 1000 meters thick) as is the case at the SNL site [1]. Thus, additional clarification of EPA definitions was required to apply our proposed strategy to the SNL site. The definitions employed in developing this monitor-well network optimization strategy are as follows:

Ground Water. Although 40 CFR 260.10 defines ground water as water in a zone of saturation, flow paths of water below the land surface in both the unsaturated and saturated zones are considered herein. Ground-water flow through the unsaturated zone must be considered to determine the location of a potential plume arriving at the water table. Therefore, ground water is defined as all water below the land surface, with the saturated zone water being the only currently regulated portion of the ground water.

Uppermost Aquifer. It may be neither feasible or necessary to consider the entire aquifer thickness when determining monitor well locations in an aquifer system of substantial thickness. Therefore, the uppermost aquifer is defined within by the flow paths between the waste site and the monitor wells. That is, the uppermost aquifer is that portion of the aquifer which could plausibly be contaminated by a release from the waste site.

Immediate Detection. "Detection" in RCRA terms involves the determination of statistical differences between contaminant concentrations in monitor wells compared to background wells when sampled at an appropriate frequency to detect a contaminant plume. A strict interpretation of immediate detection would require constant monitoring at the exact point where the contaminant reaches the water table. Instead, immediate detection is defined within as the detection of a contaminant release prior to significant deterioration of the aquifer water quality. The term "significant deterioration" is defined below.

Hydrogeologic Characterization. This term is not defined by the EPA, and is defined here as sufficient data collection and analysis to allow for the determination of ground-water flow direction and rate. Specifically, the distribution of hydraulic conductivity and hydraulic gradient are the data required for the purpose of well location. For the determination of the sampling interval, the distribution of hydraulic conductivity, the hydraulic gradient, and the effective porosity are required.

Ground-Water Flow Direction. The EPA requirements imply that the direction of ground-water flow and the direction of the hydraulic gradient are coincident. However, the direction ground water travels (the path any dissolved contaminant would follow) is controlled by the distribution of hydraulic conductivity and the hydraulic gradient. The latter definition is used here.

Ground-Water Flow Rate. Although not defined by the EPA, we propose to use the Darcy flow velocity (a volume flux defined as the volume of discharge per unit bulk area per unit time) for the purpose of well location and the seepage velocity (discharge rate per unit of pore space in a unit bulk area) for the purpose of determining the sampling interval.

The following terms are not specifically found in the regulations, but are used in developing this strategy (Figure 1):

Detection Boundary. The boundary surrounding the waste management area defined by the monitor-well network.

Significant Deterioration. A contaminant release which affects a significant portion of the aquifer.

Significant Portion of the Aquifer. This term is defined as that portion of the aquifer beyond the recovery boundary of the monitor wells. That is, any aquifer location outside the capture zones of the monitor wells. The capture zone is that area surrounding a well within which contaminants could be removed by pumping the existing monitor wells.

Recovery Boundary. The boundary defined by the capture zones of the monitor wells is herein referred to as the recovery boundary.

Finally, the assumption is made that the EPA required ground-water monitoring network is to be designed to detect a continuous type of release from the waste site. Otherwise, assuming a pulse release would require continuous sampling.

3. APPROACH TO ASSESSING COMPLIANCE

The proposed strategy for assessing compliance with the RCRA regulatory requirements is to: 1) determine if the monitor-well network is optimally located such that the wells have a high probability of detecting the likely flow paths through the saturated zone, 2) evaluate the sampling interval, and 3) assess the performance of the monitor-well network through time. Following is a description of each of these steps.

3.1. Determine Optimal Well Location

Determination of the optimum well location is based on an assessment of likely flow paths through both the unsaturated and saturated zones (Figure 2). The approach used to simulate the likely paths and evaluate the well locations is described in the following sections. Similar approaches have been used elsewhere to optimally locate a monitor-well network [2,3].

3.1.1. Determine Likely Flow Paths Through the Unsaturated Zone: The likely flow paths in the unsaturated zone, just as in the saturated zone, are controlled by the hydraulic gradient and the distribution of hydraulic conductivity (Figure 2). In the unsaturated zone, the hydraulic gradient is a function not only

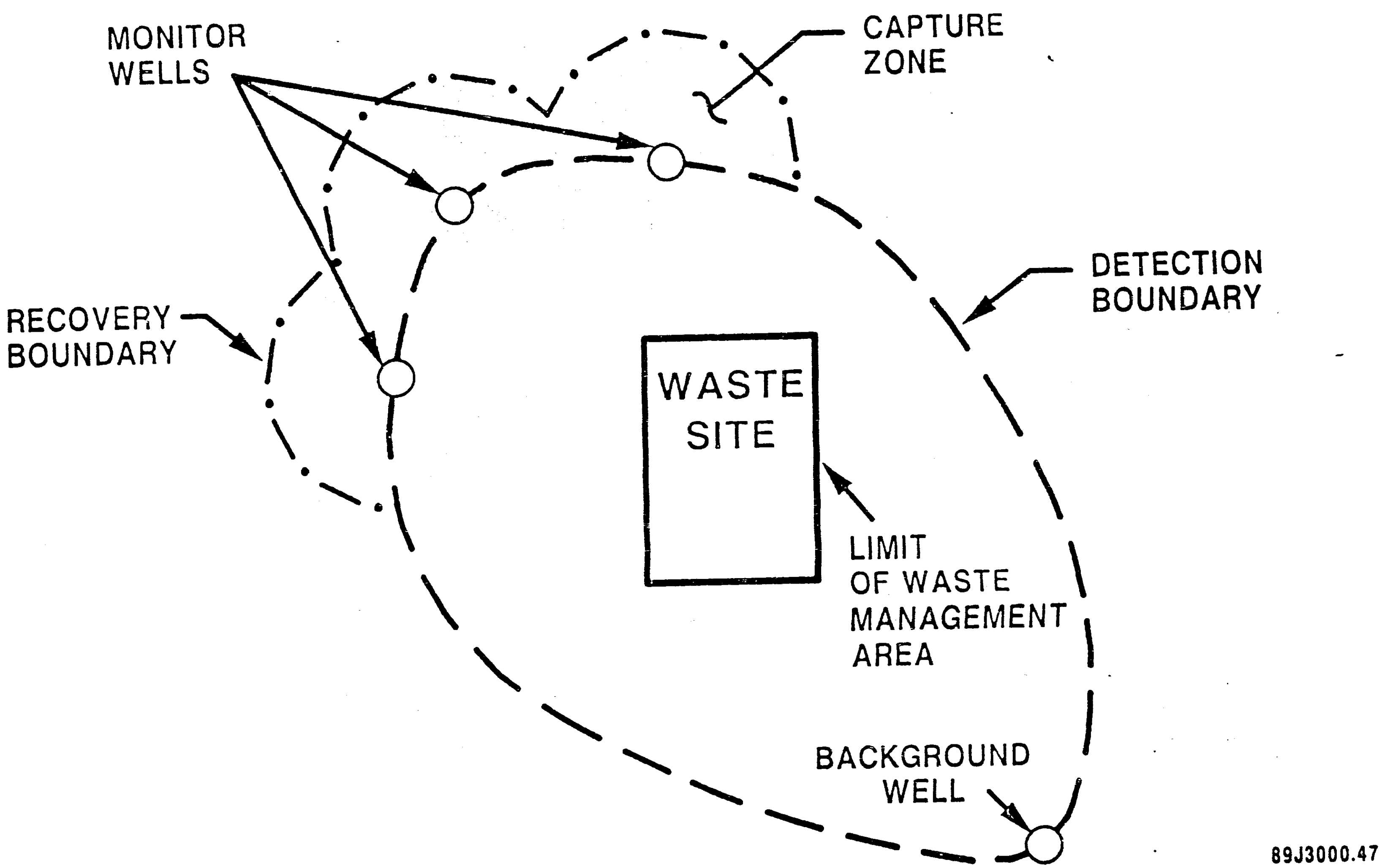


Figure 1. Illustration of some terms used to develop this strategy.

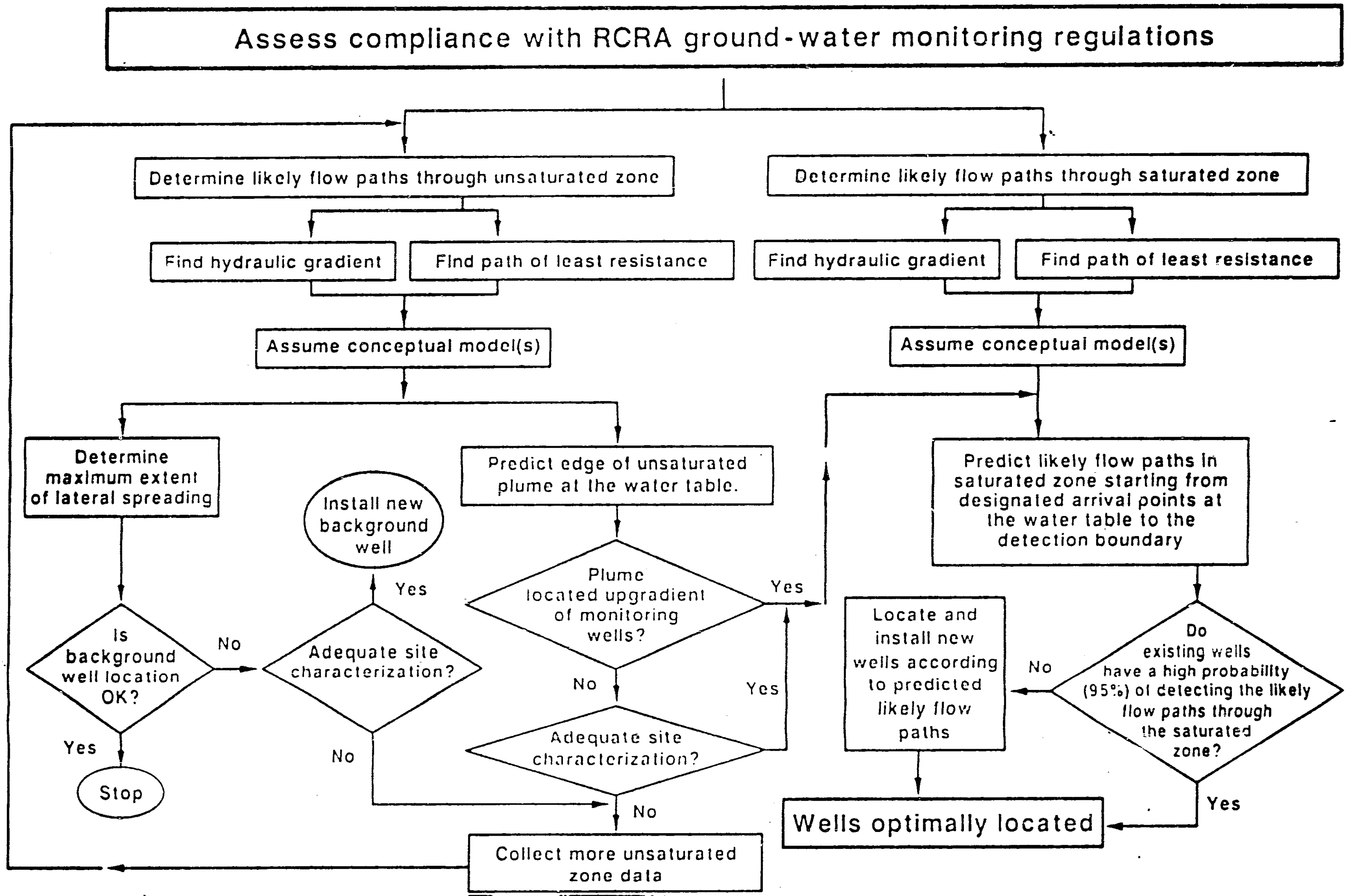


Figure 2. Approach to optimizing the monitor-well locations.

of elevation, but also of the distribution of the negative pressure head or suction. The distribution of the negative pressure head may be directly measured or inferred from a measured moisture content and the associated moisture retention curve (moisture content versus negative pressure head relationship). Alternatively, for the case of steady-state vertical flow, the hydraulic gradient can be assumed to be equal to unity.

The distribution of hydraulic conductivity in the unsaturated zone is governed by spatial variability of the geologic media and varies according to the negative pressure head. Hydraulic conductivity as a function of the negative pressure head can be determined from the saturated hydraulic conductivity, moisture retention curve, and porosity by assuming that Mualem's pore structure model applies [4].

Hydraulic gradient and hydraulic conductivity data are never complete or unambiguous. Therefore, the next step in the strategy involves making additional assumptions that describe the thickness and extent of the geologic layers, spatial variation of hydraulic properties, as well as the initial conditions and boundary conditions at the site. The sum of all of the assumptions defines the conceptual model, both here and for the saturated zone. Acceptance of the conceptual model is the key step in this strategy and should involve collaboration with the regulators.

Finally, numerical simulations which are consistent with the chosen conceptual model will be used to simulate the water movement from the waste site through the unsaturated zone to determine possible plume locations at the water table. Currently, MEAN2D [5], VAM2D [6], and DCM3D [7] are codes which could be used for the unsaturated zone numerical simulations. Uncertainty in the input parameters (hydraulic conductivity, hydraulic gradient, and porosity) will be propagated through to the model output by performing multiple conditional simulations using Latin Hypercube sampling techniques [8] to reduce the number of required simulations.

The simulated locations of the edge of the plume at the water table will be used for two purposes: 1) to determine if the location of the background well is outside the range of potential contamination, and 2) to define the starting points at the water table that will be used in simulations of the likely flow paths in the saturated zone (see Section 3.1.2). The first point requires further explanation.

To evaluate the potential for background well contamination, the numerical simulation which produces the maximum amount of lateral spreading in the unsaturated zone will be used (Figure 2). If this simulation indicates that the edge of the plume could be located between the edge of the waste site and the background well, then the background well is appropriately located to obtain samples of the ambient aquifer water quality and the background well evaluation is completed. On the other hand, the edge of the simulated plume at the water table could be located at or beyond the background well location (Figure 3). In this case, the monitor-well network may not be capable of determining a statistically significant amount of contamination (i.e., there is no statistical

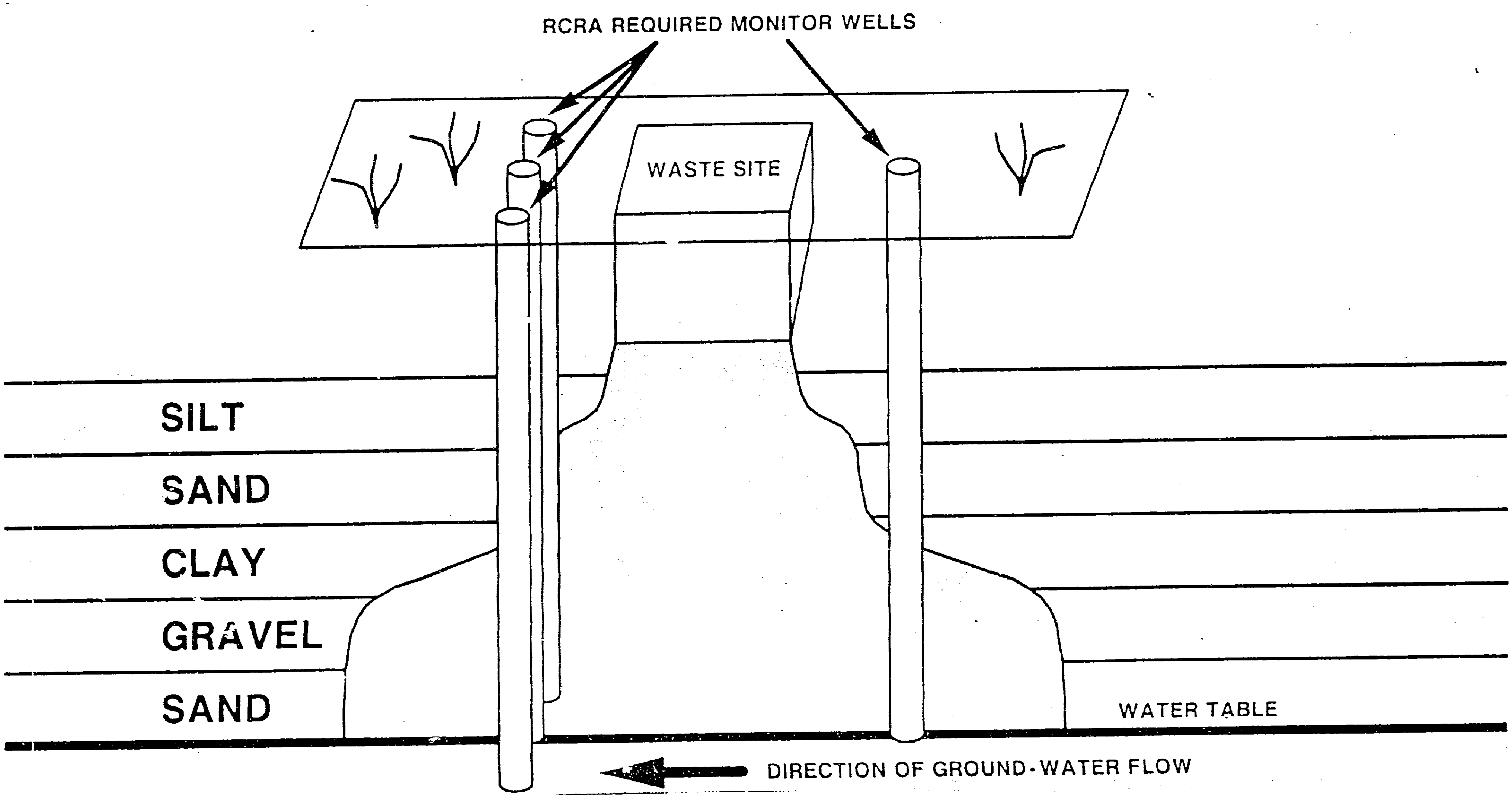


Figure 3. Possible contaminant movement through the unsaturated zone in homogeneous, layered media.

difference between the concentration of contaminant in the upgradient and downgradient monitor wells).

However, realizing that considerable uncertainty could exist in the unsaturated zone data leads to additional considerations prior to concluding that the background well is incorrectly located. Evaluation of simulation results will indicate whether or not additional unsaturated zone data could reduce the uncertainty in the simulated plume locations. If this is true, these data will be collected and the unsaturated zone analysis will be repeated. However, if the level of uncertainty in the unsaturated zone analysis can not be reduced, a new background well will be installed, the location of which is based on the simulated maximum extent of lateral spreading (Figure 2).

3.1.2. Determine Likely Flow Paths Through the Saturated Zone; Just as for the unsaturated zone, the likely flow paths in the saturated zone are controlled by the hydraulic gradient and the path of least resistance (distribution of hydraulic conductivity). In the saturated zone, the hydraulic gradient is determined from the distribution of hydraulic head. This gradient may have both vertical and horizontal components. The horizontal gradient is based on differences in water levels from wells screened only near the water table while the vertical gradient is determined by the difference in head between wells screened at different depths within the aquifer. We assume that information about the distribution of hydraulic conductivity can be determined from aquifer test data. For this problem, assessing the adequacy of an existing monitor-well network, we propose that these data should be collected by conducting several multi-well aquifer tests.

Following aquifer testing, assumptions will be made to define a conceptual model of the ground-water flow system. This conceptual model will provide the basis for the simulation of the likely flow paths in the saturated zone. Again, this is a key step in the strategy, and it should involve collaboration with the regulators.

Simulations of likely flow paths in the saturated zone will be based on numerical modeling of the ground-water flow field using the pre-defined conceptual model and will be designed to produce results that are consistent with the measured parameters (i.e., hydraulic head and hydraulic conductivity). Possible computer codes to use for the saturated zone analyses include GEOINVS [9] and USGS3D [10]. To account for uncertainty in hydrologic parameters, multiple conditional simulations will be performed, resulting in many likely flow paths from the simulated plume arrival points at the water table (see section 3.1.1) to the detection boundary.

Assessment of the existing monitor-well network is then based on the simulated plume locations relative to the well locations. If a monitor well is not located within the simulated plume, it is assumed to fail in detecting the plume. The total number of successes and failures based on all of the simulations is then calculated. In this manner, the probability of detecting the likely flow paths in the saturated zone can be determined with the existing monitor wells (Figure 4). We propose that the minimum acceptance criteria for the monitor-well network performance be set at 95% detection, however the exact value could be based on other criteria including regulatory input and cost analysis.

The results may indicate that new monitor wells are required. In this case, the simulated likely flow paths provide the information necessary to determine the number and location of additional wells (Figure 2). That is, the results show which location(s) have the highest probability of detecting the likely flow paths which were undetected by the existing network.

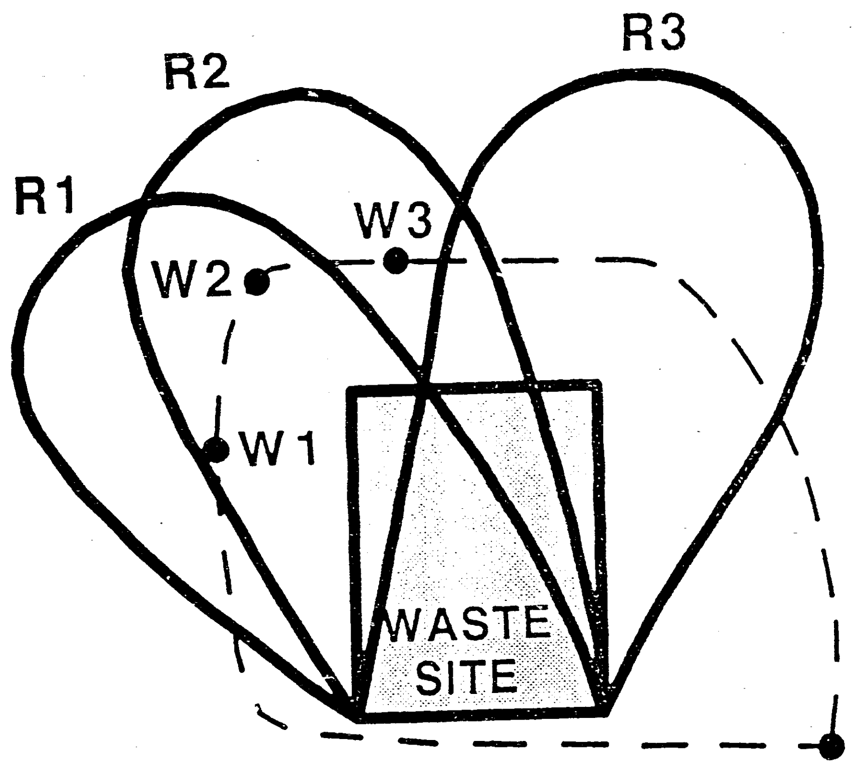
3.2. Sampling Interval Evaluation

The first part of this strategy results in an optimal monitor-well network with respect to location. Once this is accomplished, the next step is to determine the optimum sampling interval or frequency. Here the concern is to detect the movement of contaminant prior to significant deterioration of the aquifer water quality. The RCRA regulations state that the wells must be sampled, at a minimum, quarterly for the first year and semi-annually thereafter. Whether or not the minimum required sampling times are adequate can only be determined by an analysis of likely contaminant travel times. Therefore, the sampling interval is based on the regulatory requirements as a minimum frequency and on expected contaminant travel times for the maximum frequency (Figure 5).

A conservative approach was taken in order to determine an adequate sampling frequency. The contaminants were assumed to be moving at the average ground-water velocity (i.e., no retardation or degradation occurs) in the direction of likely ground-water flow. It was also assumed that there is no dispersion other than that caused by the defined spatial variability of hydraulic conductivity. Both of these assumptions lead to conservative results; shorter ground-water travel times and more frequent sampling.

The appropriate sampling interval was assumed to be less than or equal to the shortest travel times across any of the capture zones of the monitor wells. That is, we assumed that the contaminant to be detected lies at the edge of a capture zone at the time of the previous sampling so that the contaminant was not detected during the last sampling event. The contaminant should be detected before it travels past the outer edge of the capture zone of the monitor wells. By not allowing "significant deterioration of the aquifer" to occur, the existing monitor-well network could aid in cleaning up the plume.

This minimum travel time can be calculated from combining particle tracking with the previous saturated zone likely flow path simulation results (Section 3.2.1). The only additional data required for this step are the range of effective porosities which can be estimated from the literature according to the known lithology of the aquifer, geophysical logging results, or core laboratory testing. Uncertainty in the input parameters (hydraulic gradient, hydraulic conductivity, and effective



WELLS	HITS 1	2	3	DETECTED
REALIZATION 1	1	1	0	1
2	1	1	1	1
3	0	0	0	0
⋮				
1000				
TOTAL DETECTED				950

$$\text{PROBABILITY OF DETECTION} = \frac{950}{1000} = 95\%$$

Figure 4. Approach to calculating the probability of detecting likely flow paths in the saturated zone. Realizations depict possible plume locations.

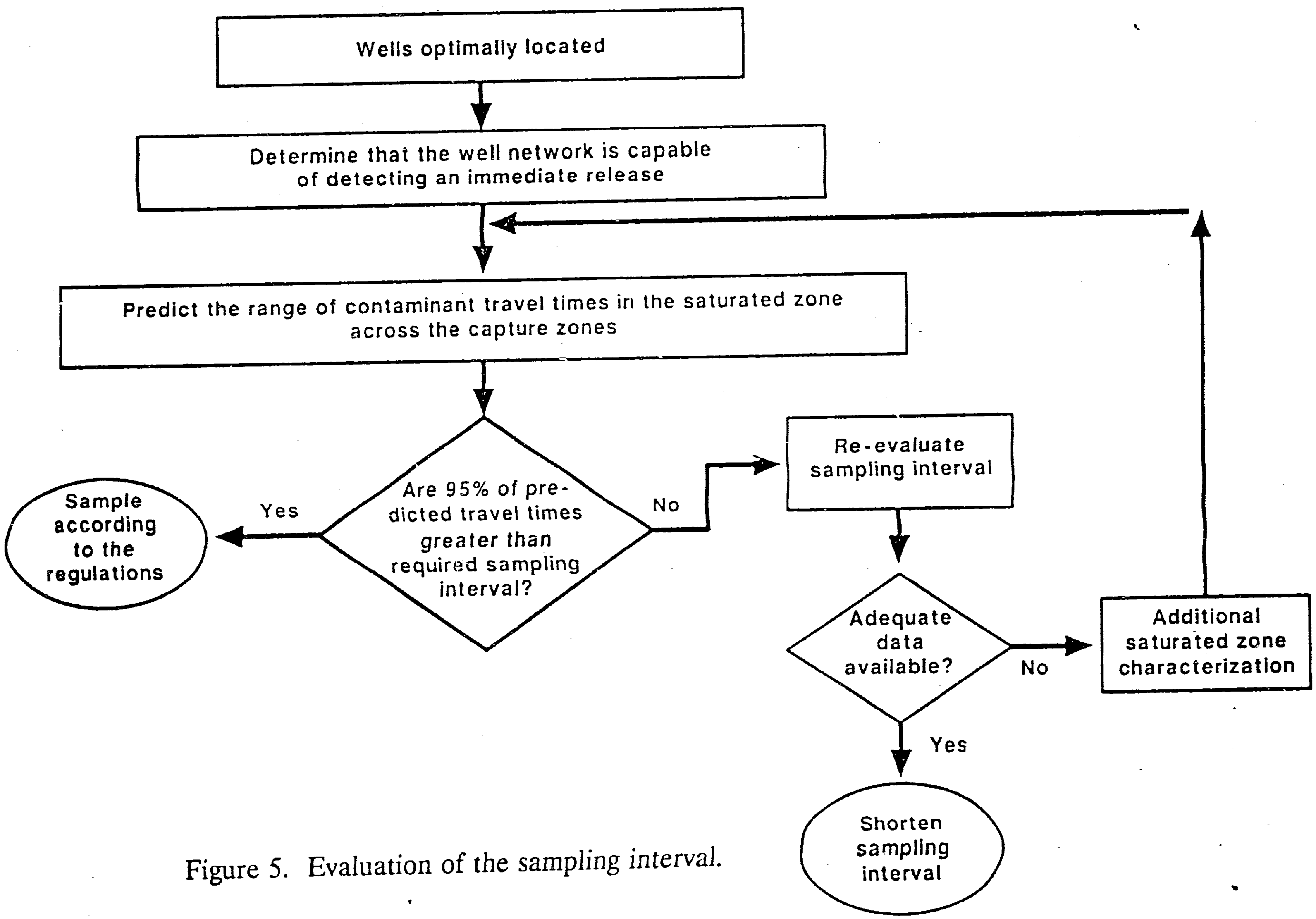


Figure 5. Evaluation of the sampling interval.

porosity) will be accounted for by conducting multiple simulations of the travel time across the capture zones of each well, resulting in a range of possible contaminant travel times (sampling intervals).

If at least 95% of the estimated contaminant travel times across the capture zones are greater than the required sampling interval, the regulatory ground-water sampling schedule will be followed. If not, then it is necessary to re-evaluate the sampling interval. The regulatory ground-water sampling schedule will continue to be followed during the period of re-evaluation. Prior to shortening the sampling interval to less than the EPA requirements (sampling more frequently), evaluation of the travel time results will indicate whether or not the collection of additional and/or more site specific data would reduce the uncertainty in the simulated travel times. If this is true, additional data will be collected and the travel time analysis will be repeated. However, if uncertainty can not be further reduced, then the sampling interval should be shortened (Figure 5).

3.3. Assessing Changes in the Monitor-Well Network Through Time

The monitor-well network that results from the previous steps will have been based on present and past hydrologic conditions, including consideration of seasonal fluctuations that are documented in the existing records. However, hydrologic conditions may change in the future due to such factors as long-term environmental changes, or long- and short-term human-induced changes. EPA requires that the monitor-well network will continue to be able to "immediately" detect a release from the waste site even if such changes exist. Our approach to insuring the adequacy of the monitoring network with time is based on understanding the cause of the hydrologic change and assessing potential changes in the flow-path directions and ground-water travel times (i.e., the possible contaminant travel paths) resulting from the change.

This approach is not solely based on changes in the hydraulic gradient. Instead, determination of the cause of change is necessary for defining a course of action. Specifically, we want to be able to distinguish between one time perturbations to the system versus permanent or long-term changes to the system. For example, the simple activity of performing an aquifer test at the waste site could change the direction of the hydraulic gradient by pumping a well or wells for a short time. After pumping was discontinued, the hydrologic system would return to its original gradient. In this case, a contaminant would only travel a very short distance under the altered gradient while over a larger time (i.e., the sampling interval), the contaminant would travel to the monitor wells. Thus, it is unnecessary to drill additional wells. On the other hand, long term or permanent changes to the hydrologic system which adversely affect the performance of the monitor-well network may have to be accounted for by drilling one or more additional monitor wells. If we are unable to determine the cause and the nature of the change then additional wells will be installed. The following procedure will be followed in assessing the adequacy of the monitor-well network with time (Figure 6).

The performance of the monitor-well network will be evaluated after each sampling event as described in Section 3.1.2. First, if the probability of detecting a plume at the existing wells drops below 95% (see Section 3.1.2), the frequency of water-level monitoring will be increased while possible causes for the change in the monitor-well network performance are investigated. Then, if the existing wells still do not have a 95% probability of detecting the likely flow paths through the saturated zone after two consecutive sampling intervals, a decision will be made as to whether a new monitor well is required. A new monitor well or wells will be installed if the cause of the change is unknown or if the change is known to be permanent.

If the cause of the change is known to be temporary relative to the sampling interval, then the only action taken would be to continue water-level monitoring to assure that the change was temporary. The remaining case is that the cause of the change is not permanent but extends past two sampling intervals. Then the decision on whether or not to drill a new well should be based on the expected plume location after two sampling intervals. New wells would be added only if the likelihood of detecting this plume with existing wells would be less than 95% (Figure 6).

4. DISCUSSION

Using current EPA guidance [11], neither the owner/operator nor the regulator have a clear method of determining the adequacy of a monitor-well network with respect to the number of wells, well location, and sampling frequency. The owner/operator often feels that the regulator has a very limited basis for requesting additional wells while the regulator feels that EPA has not provided sufficient guidance for evaluating how many wells are necessary. Both parties may acknowledge that the process is very subjective fro start to finish. This proposed strategy provides a framework for the owner/operator and the regulator to agree upon the required number and location of monitor wells, the sampling frequency, and the monitor-well network performance through time.

This strategy attempts to minimize the current subjectivity associated with monitor-well network evaluation, but subjectivity in the evaluation is in no way eliminated. Instead, the subjective aspects of the evaluation process are moved up front where they can be jointly addressed by the owner/operator and the regulator. Specifically, the subjective components arise in the conceptual model development stage and in determining the adequacy of the data. These two components are currently part of every step in the monitor-well network evaluation problem, beginning with the first well drilled and continuing each time new data (i.e., quarterly or semi-annual water-level measurements) are collected. In any case, the owner/operator and the regulator must resolve differences of opinion over these issues. Using this proposed strategy, the subjective decisions are made only at the onset of the problem. From the point of agreement on the

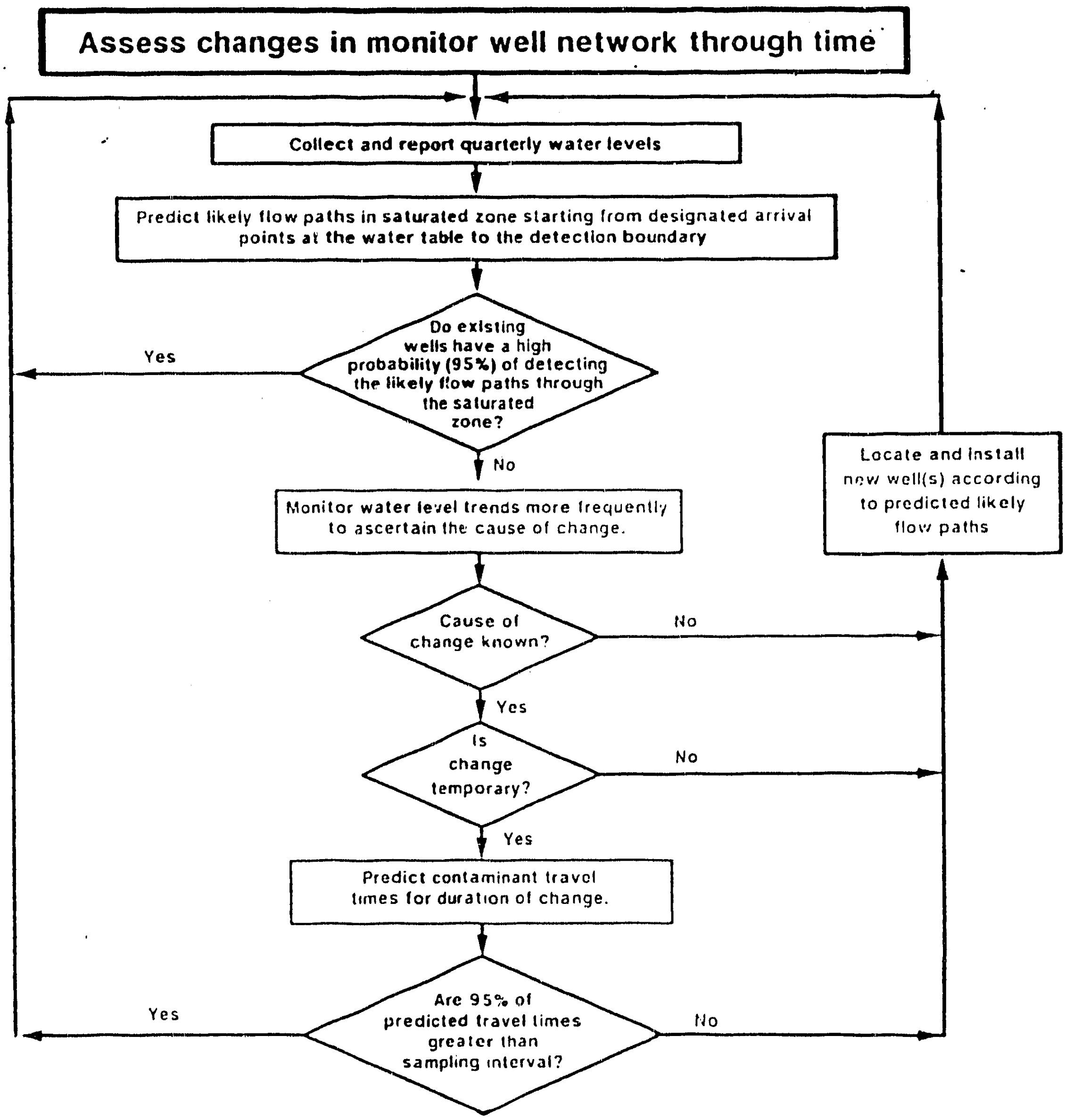


Figure 6. Approach to assessing changes in the monitor-well network performance through time.

conceptual model, data adequacy, and performance measures, the numerical model results will indicate whether or not the monitor-well network is adequate.

This proposed strategy is based on the acknowledgement of uncertainty both in our understanding of the ground-water flow system and the parameters that describe the system. In addition, this approach provides a framework for combining the EPA ground-water monitoring requirements with the requirements for aquifer characterization.

5. SUMMARY

To satisfy the RCRA ground-water monitoring regulations, a waste site must have a ground-water monitoring system consisting of a minimum of one upgradient and three downgradient wells and demonstrate that the downgradient wells have an acceptable probability of detecting a statistically significant amount of contamination at the water table from now until at least 30 years after site closure.

A strategy has been presented here for assessing compliance with these RCRA ground-water monitoring regulatory requirements at a specific SNL waste site. The proposed strategy provides a mechanism which allows the owner/operator and the regulators to determine the adequacy of an existing monitor-well network. Additional clarification of some EPA regulatory definitions was required to develop this strategy for application to a waste site at SNL because the EPA regulations do not account for many of the hydrogeologic complexities associated with the arid southwest.

Multiple interactions between the owner/operator and the regulator are required to implement this proposed approach. The strategy attempts to minimize the current subjectivity of the monitor-well network evaluation process by prior agreement to a set approach and by defining the performance measures to evaluate the monitor-well network. In addition, conceptual model development is a key step which should involve collaboration with the regulators.

This strategy is based on the determination of likely ground-water flow paths through both the unsaturated and saturated zones and ground-water travel times. The general approach involves: 1) determining that the monitor-well network is capable of detecting 95% of the likely flow paths in the saturated zone and that the background well is located such that it monitors ambient conditions, 2) assuring that no contaminant travels beyond the capture zones of the monitor wells in between sampling events, and 3) assessing whether the monitor-well network performs adequately through time.

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