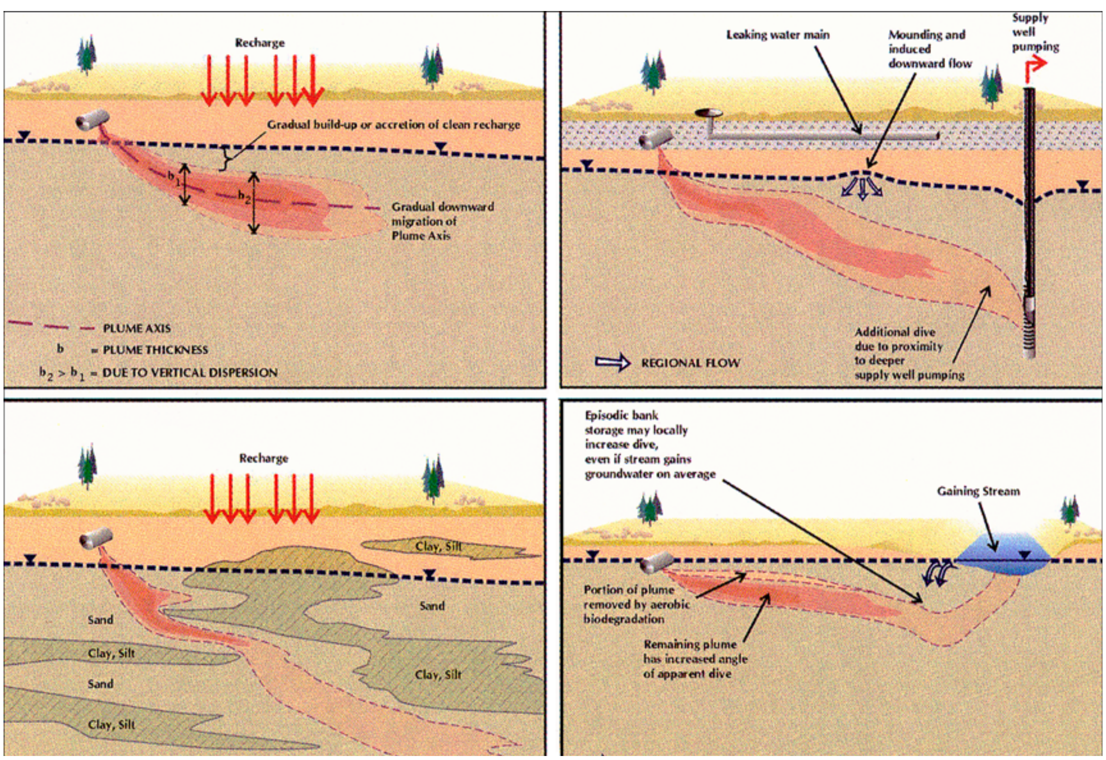
Downward Solute Plume Migration: Assessment, Significance, and Implications for Characterization and Monitoring of "Diving Plumes"

Regulatory Analysis and Scientific Affairs

API SOIL AND GROUNDWATER TECHNICAL TASK FORCE
BULLETIN 24
APRIL 2006



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EXECUTIVE SUMMARY

The objective of this technical bulletin is to promote a common understanding of the phenomenon of diving plumes. The term “diving plume” refers to the gradual downward vertical migration of a dissolved-phase contaminant plume to greater depths in the subsurface with increasing distance along the flow path, resulting in the existence of a region of uncontaminated water overlying portions of a contaminant plume:

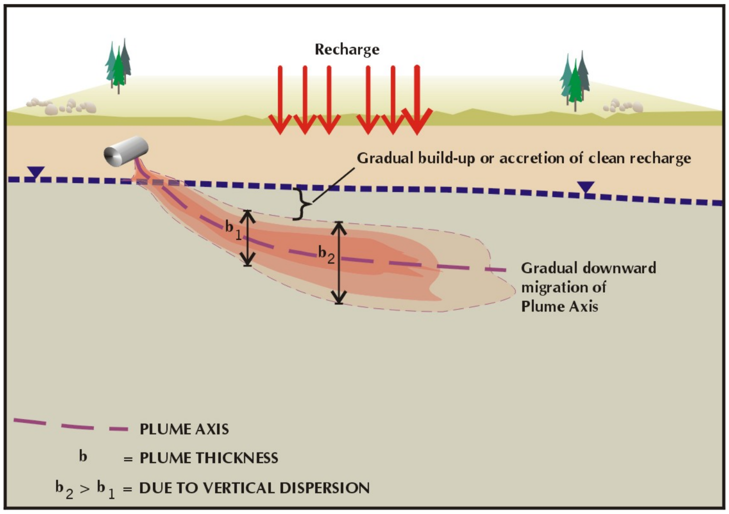

Figure 1. Example of a Diving Plume due to Accretion of Clean Recharge

Diving plumes have several implications for site characterization. As the magnitude of gradual plume dive increases, chemicals may migrate below shallow monitoring well screens and go undetected at sites with monitoring networks that rely on single well screens positioned near the water table. The presence of clean water in wells screened across the water table could be misinterpreted if the potential for plume dive at the site is not understood. An unrecognized diving plume could result in an inadequate evaluation of risk to receptors, erroneous interpretation of the significance of natural attenuation, under-design of a remediation system or inadequate assessment of remedial performance.

The factors that control groundwater flow direction (and therefore, any resulting plume dive) are largely independent of the solutes comprising a dissolved-phase plume. In addition, although the vertical dispersivity of an aquifer affects the amount of vertical spread of a plume, and the amount of spreading that occurs below the water table with distance from a source, the net vertical migration of a plume as a whole depends on several hydraulic, geologic, and biogeochemical processes.

The major hydraulic factor controlling plume dive is the existence of naturally occurring or anthropogenically induced vertical hydraulic gradients. Although a downward vertical gradient indicates the potential for plume dive, it does not by itself indicate the rate or degree, if any, of the resulting plume dive.

The depth to which a plume will dive in an unconfined aquifer as a result of natural or anthropogenic recharge is dependent on the recharge rate and the groundwater seepage velocity. The influence of recharge on a diving plume compounds with increasing distance from a contaminant source. Generally, greater recharge rates will result in a greater magnitude of dive, but the recharge effects will be less at higher seepage velocities.

Groundwater supply wells that extract groundwater at depth induce downward vertical gradients in overlying strata, and can induce downward plume migration in the absence of effective confining units or aquitards.

Geologic factors that influence vertical plume migration include variable layered lithology, which results in variations in hydraulic conductivity in the subsurface; strata orientation and dip angle; and heterogeneity within the aquifer. Each of these factors can result in preferential flow paths leading to increased vertical migration.

Biogeochemical factors can result in spatial variations in contaminant attenuation mechanisms, which may give the impression that a plume is diving or diving at a greater angle than would be observed solely because of recharge accumulation. Biodegradation, for example, can be enhanced in shallow groundwater as a result of increased oxygen loading via groundwater recharge.

Several methods are available to assess the potential for and characterize the magnitude of dive prior to or during a detailed field investigation. Analytical tools include using the ratio of recharge rate to groundwater discharge rate to estimate the expected slope of dive, or the depth to which a plume will dive below monitoring well screens for given distances. The U.S. Environmental Protection Agency (U.S. EPA) provides an on-line calculator that estimates the position of the phreatic surface, streamlines, and anticipated slope of dive for specified combinations of boundary heads, recharge rate, and aquifer hydraulic properties. Many existing numerical models will also simulate the position of the potentiometer surface, streamlines, and the three-dimensional distribution of a contaminant plume.

A tiered approach is necessary to evaluate a site's potential for diving plumes. As with any risk-based characterization effort, the effort level should commensurate with the threat level to receptors. As such, preliminary characterization levels of diving plumes should include an evaluation of the dive potential, followed by application of simple analytical calculations to estimate the magnitude of potential dive. If preliminary screening evaluations and results of analytical calculations indicate a potential for plume dive that leads to unacceptable risk to receptors, then detailed field characterizations should be performed. Additionally, field characterizations should also be conducted in a phased-approach consistent with the level of risk to receptors (API 2000). However, it is important to note that at most sites, dissolved-phase plumes consist of solutes that readily sorb, degrade, and otherwise attenuate such that they are relatively small in horizontal and vertical extent and therefore are generally not subject to mechanisms of downward migration that leads to significant plume dive. As such, tiered, risk-based approaches to characterization are the key factor to assessing risk to receptors based on the potential for plume dive.

To assess the potential for plume dive at a site, and to avoid mis-characterizing a diving plume, consider the following steps as part of a risk-based site characterization strategy:

1. Evaluate potential threats to current and future groundwater and surface water receptors:
    - determine beneficial uses of groundwater and potentially affected surface water
    - determine density and proximity of supply wells, vertical separation between site and screened intervals, presence of impermeable units
    - evaluate the potential for impacted groundwater to discharge to surface water
2. Refine the Site Conceptual Model (SCM) by assessing if hydraulic, geologic, or biogeochemical conditions at a site indicate the potential for plume dive:
    - determine the significance of the site location relative to areas of potential recharge and discharge within the watershed
    - determine pumping rates and assess the potential for wells to acts as vertical conduits
    - assess the presence, direction, and magnitude of vertical gradients
    - obtain information on site lithology – evaluate regional geology and local stratigraphy, identify lithologic types, likelihood of heterogeneity (preferential flow paths and/or trends in hydraulic conductivity with depth), evaluate if strata are dipping
    - review available literature for nearby sites or sites with similar hydrogeologic conditions and assess the significance of diving plumes in those conditions

3. If preliminary evaluation of site conditions indicates the potential for plume dive and if threats to receptors are moderate to high, use analytical tools (some of which are discussed in this bulletin) to further assess the potential for plume dive, and to guide further site characterization.
4. If the preceding steps indicate plume dive may be significant, and threats to receptors are moderate to high, a more detailed level of characterization may be warranted:
    - analytical and/or numerical models may guide or assist with monitoring well installation – locations and appropriate depths
    - depth-discrete monitoring techniques can be used to characterize the horizontal and vertical extent of a plume and evaluate the likely transport path of the plume
    - geophysical methods can identify the more permeable zones which will allow groundwater and solutes to preferentially flow through.

Key Points Discussed in this Bulletin

Implications of Missing Diving Plumes:
- Inadequate evaluation of risk to receptors
- Under-designing remedial actions
- Inadequate assessment of remediation performance

Primary Factors Affecting Plume Dive:
- Hydraulic –high recharge infiltration rates, strong downward vertical gradients, nearby deep supply well pumping, anthropogenic effects such as short-circuiting around wells or leaky water mains
- Geological - dipping strata, preferential flow paths, absence of low permeability confining layers or anisotropy
- Biogeochemical – vertical concentration gradients caused by biodegradation near the water table giving the appearance of plume dive

Methods to Assess Diving Plumes:
- Field Characterization Techniques
- Biodegradation Assessment
- Simple Analytical Models
- Numerical Models

INTRODUCTION

The term "diving plume" refers to the gradual vertical migration of a dissolved-phase contaminant plume to greater depths in the subsurface with increasing flow path distance. Although plume thickening along flow paths occurs as a function of vertical spread from hydrodynamic dispersion, diving plume processes refer to hydraulic and/or geologic conditions that result in the existence of a region of uncontaminated water overlying portions of a contaminant plume (Figure 1). Additionally, some plumes may appear to dive as a result of spatial variations in biogeochemical conditions (e.g., enhanced biodegradation near the water table) where aerobic conditions sometimes occur (Landmeyer and Bradley 2003).

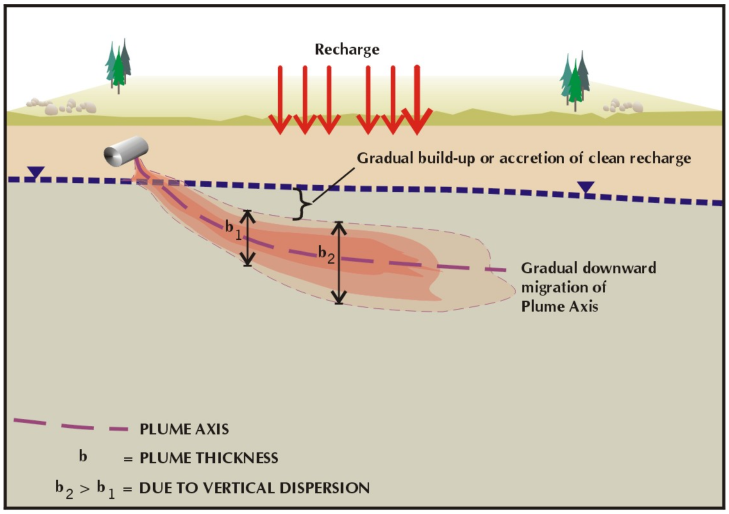

Figure 1. Example of a Diving Plume due to Accretion of Clean Recharge

The factors that control groundwater flow direction (and therefore, any resulting plume dive) are largely independent of the solutes comprising a dissolved-phase plume. This paper discusses the downward migration of dissolved-phase plumes as a result of geologic, hydraulic, and/or biogeochemical factors and is distinguishable from sinking free-phase mixtures referred to as dense non-aqueous phase liquids (DNAPLs). Therefore, any solute plume, whether it originates from light nonaqueous phase liquids (LNAPLs) or DNAPLs, is potentially subject to geologically or hydraulically induced vertical migration.

For most trace organic contaminants, the density of the dissolved chemical does not affect the tendency for a plume to dive. Density-driven flow of dissolved plumes becomes important only when chemical concentrations are such that the density of the groundwater/solute mixture becomes significantly greater than the density of water (for many common organic compounds such as MTBE and benzene, toluene, ethylbenzene, and total xylenes (BTEX) would require concentrations greater than the chemical's effective solubility). Although LNAPLs may float and DNAPLs may sink when in pure phase, the constituents that dissolve from these free-phase mixtures into groundwater are neutrally buoyant.

Dive is typically more evident in longer and older dissolved-phase plumes. MTBE is often associated with the phenomena of "diving plumes" because it is highly soluble, does not sorb significantly, is often slow to biodegrade, and consequently will often migrate greater distances from a source than other LNAPL constituents such as BTEX.

If the magnitude of dive is significant, chemicals may migrate below shallow monitoring well screens and go undetected at sites with monitoring networks that rely on single well screens positioned near the water table. Several implications arise from missing a diving plume. If a diving plume is not adequately characterized, samples collected from water table wells screened in the overlying accumulation of clean groundwater may be falsely interpreted, which could lead to inadequately characterizing risk to receptors, or overestimating the significance of natural attenuation. Additionally, inadequate characterization can result in a greater potential for under-designing remediation systems, and inadequate assessment of remedial performance. As such, development of a Site Conceptual Model (SCM) is important to assess site conditions and identify the potential for plume dive, and evaluate potential risks to receptors.

If clean water overlies a portion of a contaminant plume, this may greatly reduce the potential for volatile emissions from the plume into soil gas and subsequent subsurface vapor intrusion into overlying buildings. Therefore, characterization of the magnitude of plume dive can assist in assessing the potential for subsurface vapor intrusion.

The phenomenon of plume diving has been observed at several detailed field studies throughout the United States. Plume dive as a function of gradual build-up or accretion of recharge has been noted at several sites located in Long Island, New York (Weaver and Wilson 2000; Weaver et al. 1999). At one site, comparison of MTBE analytical results from depth-discrete monitoring wells to vertically averaged results falsely indicated that although averaged concentrations fell below New York State's threshold value of 10 µg/l, significant concentrations of almost 8,000 µg/l occurred at depth in the downgradient portions of the aquifer. In addition, the benzene plume appeared to be shortened to approximately 1/3 of its actual length, and the averaged concentrations falsely indicated no chromatographic separation of the benzene and xylene plumes (this is inconsistent with the expected and observed attenuation behavior of these constituents). At another site, downward migration of constituents was further induced by nearby supply well pumping from deeper aquifers.

At a South Carolina site, higher concentrations of MTBE and benzene occurred in the deeper sampling ports of multilevel monitoring wells in an area below a drainage ditch as a result of recharge events that deflected originally horizontal groundwater flow patterns (Landmeyer et al. 1998; Lahvis et al. 2003). Studies done at a site in Cape Cod, Massachusetts, indicate accretion of precipitation, rather than hydrodynamic dispersion, was the dominating factor controlling vertical migration of a VOC plume (Reynolds et al. 1991).

Stratigraphy can also influence plume behavior. At a site in western Kansas, an MTBE plume in the shallow portion of the water table aquifer near the source migrated downward along preferential pathways (Hattan and Blackburn 1999). In California, a natural gradient tracer experiment on an MTBE plume at the U.S. Naval Base Ventura County, Port Hueneme, indicated the plume center of mass deepened with migration distance because of the dip of the stratigraphy (Amerson and Johnson 2003).

The U.S. EPA Region 5 has conducted research on how to best monitor leaking underground storage tank (LUST) sites to characterize diving MTBE plumes. Results at three sites in the Midwest (Illinois, Wisconsin, and Michigan) indicate higher concentration plume "cores" at progressively deeper intervals with distance from the source as a function of recharge area and/or changes in lithology at the water table. (Alvarez, 2003).

The objective of this technical bulletin is to promote a common understanding of the phenomenon of diving plumes. The following sections discuss the factors that can cause plumes to dive, show methods used to evaluate the potential for and magnitude of diving plumes, and provide suggestions regarding the identification and characterization of diving plumes.

FACTORS CONTROLLING DIVING PLUMES

Diving plumes occur as a result of several hydraulic, geologic, and biogeochemical factors. Although each of these factors contributes individually to the potential for plumes to dive, they may act in combination to influence the overall groundwater flow field and the distribution of contaminants in the subsurface. This section discusses each of these factors and describes how each influence the potential for plumes to dive.

Hydraulic Factors

One of the most important hydraulic factors controlling plume dive is the presence of downward vertical hydraulic gradients, i.e., lower potentiometric head at greater depths. Vertical gradients result from the combined influence of many natural and anthropogenic factors. Natural factors include variations in the magnitude and distribution of surficial recharge, or location within a watershed containing groundwater discharge to or recharge from surface water bodies, or stratigraphic controls on groundwater flow (Figure 2). Anthropogenic factors may include induced flow from pumping wells or short-circuiting around improperly completed monitoring and/or pumping wells; mounding beneath septic leachfields, leaking water mains, or infiltration and recharge basins; and short-circuiting of groundwater within excavations, wells, or utility corridors.

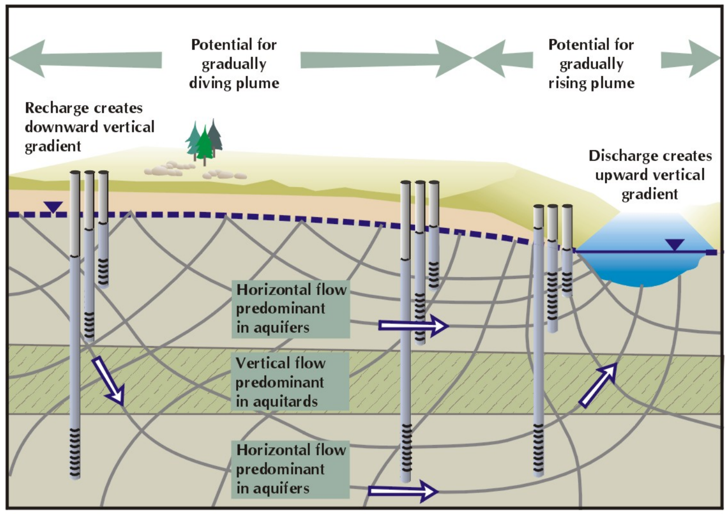

Figure 2. Expected groundwater flow conditions within a watershed

A downward vertical gradient indicates the potential for plume dive, but it does not by itself indicate the rate or degree, if any, of the resulting plume dive. The hydraulic gradient provides information regarding the potential flow direction, but does not by itself indicate the water flow magnitude. Darcy's Law (the accepted framework for estimating the flow of water through porous media) states that flow through a cross-sectional area is the product of the hydraulic gradient and the hydraulic conductivity. For example, strong downward gradients (0.1 to 1 ft/ft), in combination with very low vertical hydraulic conductivity may result in little or no observable plume dive. Conversely, small vertical gradients (<<0.1 ft/ft), in combination with relatively high vertical hydraulic conductivity may result in significant plume dive.

The depth to which a plume will dive in an unconfined aquifer is partly dependent on the rate of recharge to the aquifer. In general, greater recharge rates cause a greater induced vertical gradient, and therefore a greater degree of plume dive. The influence of recharge on a diving plume compounds or accumulates as a function of distance from a contaminant source (refer back to Figure 1). Plume dive from recharge also depends on the overlying land use or cover, as seen with the diving plumes on Long Island (Weaver et al. 1999). They observed an increase in the rate of plume dive where the land surface is exposed, and where greater recharge to groundwater occurred because of the presence of an overlying gravel pit.

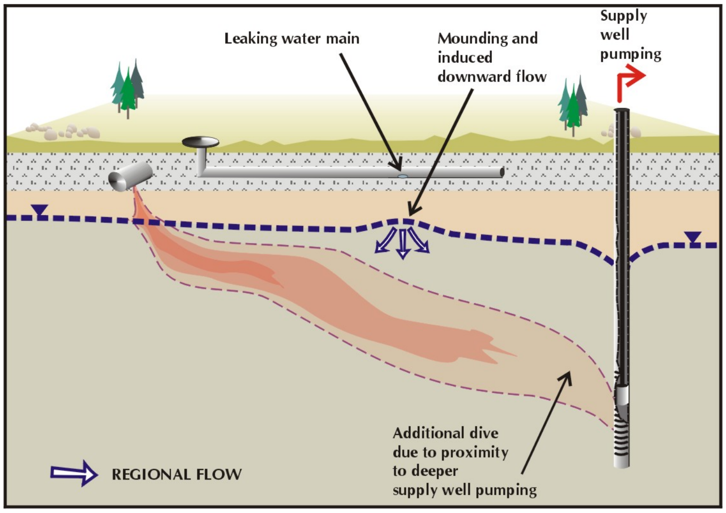

Figure 3. Example of a Diving Plume Along Leaking Water Main and Supply Wells

Anthropogenic factors that increase the recharge rate and induce vertical gradients can cause plumes to dive, sometimes over large areas such as from irrigated fields, groundwater injection wells or spreading basins, or smaller areas such as from leaking water mains and sewer pipes (Figure 3). In addition, groundwater supply wells that extract groundwater at depth induce downward vertical gradients in overlying strata and result in downward groundwater flow in the absence of effective confining units or aquitards (Figure 3). In geological conditions that are conducive to plume dive, the closer a plume is to the screened interval of an underlying pumping well, the greater the degree of plume dive because of the converging nature of groundwater flow to a well. However, it is important to confirm the integrity of pumping well completions, because pumping wells that are not properly sealed may result in short-circuiting of a plume. The plume could migrate directly downward along an improperly completed wellbore, resulting in the apparent dive of a plume due to pumping.

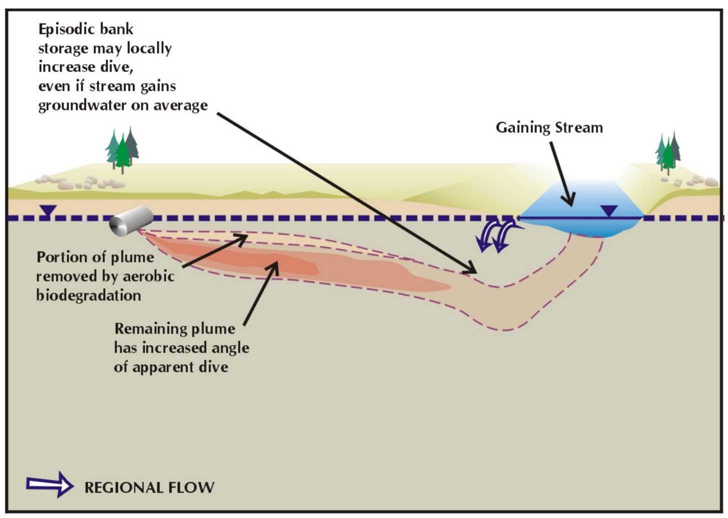

Figure 4. Example of a Diving Plume Near a Gaining Stream

Groundwater-surface water interaction and the location of recharge and discharge areas influence groundwater flow patterns and plume dive. In areas where surface water discharges to groundwater (recharge areas or losing reaches), downward gradients are present and enhance the downward migration of plumes. In areas where groundwater discharges to surface water (in a discharge area or a gaining reach), plumes may migrate upwards toward the surface water body. A plume may appear to dive near a gaining reach of a river, if bank storage occurs during periods of high river stage (Figure 4).

<u>Geologic Factors</u>

Some depositional environments possess conditions that may influence vertical plume migration, including layering of materials of different hydraulic conductivity, strata orientation and dip angle, and degree of heterogeneity of the aquifer. Each of these conditions can result in preferential flow paths leading to increased vertical migration.

Layering of different lithologies (e.g., sand silt and clay) results in variations in hydraulic conductivity within the subsurface. In depositional environments that resulted in fining upward sequences, more permeable sediments are located at greater depths, which, in combination with prevailing hydraulic conditions, may result in downward vertical gradients. If higher permeability sediments are located below the water table, contaminants released near the water table will likely migrate toward the units that have a greater capacity to transmit water and contaminants.

The greater the degree of heterogeneity in the subsurface, the greater is the potential for preferential migration pathways. Alluvial or fluvial environments usually consist of more permeable sands and gravels interbedded with less permeable silts and clays. Groundwater and contaminants may flow preferentially downward or upward if flow paths divert around less permeable silt and clay lenses (Figure 5), or if flow paths follow a bifurcating sand deposit. The magnitude of heterogeneity-induced dive may be more easily observed with time or with increasing seepage velocity, since longer plumes occur under these conditions.

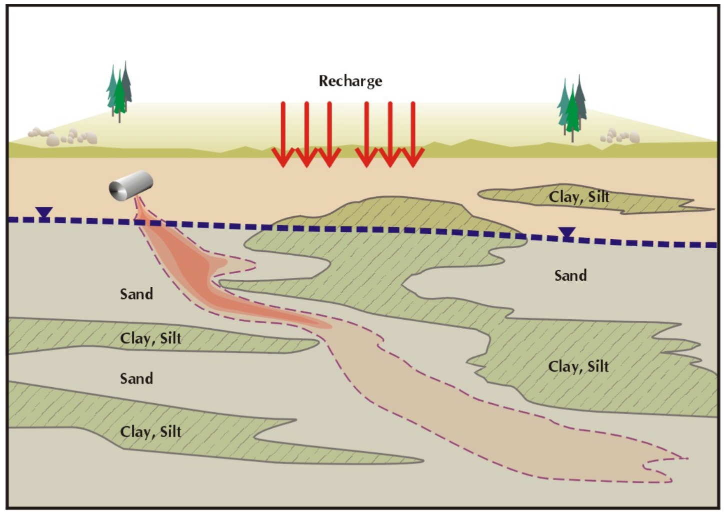

Figure 5. Example of a Diving Plume due to Stratigraphic Controls

Strata orientation and dip angle also influence plume migration, as seen in the example of the MTBE plume at Port Hueneme (Amerson and Johnson 2003). Natural gradient tracer experiments indicated the plume was migrating along a dipping sand unit bounded above by clay.

Biogeochemical Factors

Biogeochemical processes can result in spatial variations in contaminant attenuation mechanisms, which may give the impression that a plume is diving or that it is diving at a greater angle than would be observed solely as a result of recharge accumulation. If the recharge water infiltrating into the subsurface contains greater amounts of dissolved oxygen, aerobic degradation may be enhanced near the water table. The effects of dissolved oxygen with depth on apparent plume dive have been noted by Landmeyer and Bradley (2003). Episodic infiltration of rainwater influenced dissolved oxygen concentrations in wells screened a few feet below the water table. In the unpaved portion of the site, the plume dove gradually as a result of precipitation accumulation, but the apparent dive was greater than would have occurred solely from hydraulic effects because of enhanced biodegradation near the water table (refer to example in Figure 4).

Other Factors

In general, the horizontal and vertical extent over which dive occurs is a function of time and distance of migration. Plume mobility, and therefore the rapidity of dive, is influenced by the rate of attenuation, which depends on the chemical properties of the constituent and subsurface biogeochemical conditions. A greater degree of plume dive can occur over time as sources age and contaminants have migrated over greater distances. Although the occurrence of geologically and hydraulically induced plume dive is independent of chemical properties, solubility and degradation influence plume extent and therefore the opportunity for and magnitude of plume dive. More soluble, mobile constituents that do not readily degrade will migrate greater distances from sources, increasing the potential for plume dive as a function of stratigraphy, infiltration of recharge, or other mechanisms.

The interpretation and appearance of dive may be affected by the type, extent, and age of the source zone, and whether or not the source has been removed or contained. A relatively thin source zone, as may occur from a small accumulation of LNAPL or DNAPL, or from a non-NAPL source, will tend to create a similarly thin plume. The dive of such a plume may be easier to observe in the field using depth-discrete monitoring techniques. Conversely, a relatively thick source zone, as may occur from a large accumulation of NAPL, or one that has been distributed over a large depth interval by historical water level fluctuations, or one created from multiple releases occurring at time periods with different depths to groundwater, will tend to create a thicker and potentially more complex plume. The dive of such a plume may be more difficult to resolve in the field.

In assessing the degree to which a plume may dive, the vertical dispersion characteristics of an aquifer should be considered. An aquifer with high vertical dispersivity is likely to cause a higher degree of plume thickening relatively close to its source, whereas an aquifer with low vertical dispersivity is likely to result in thinner plumes with a greater degree of overlying, accumulated clean recharge water.

METHODS FOR ASSESSMENT OF PLUME DIVE

There are several methods available to assess the potential for and characterize the magnitude of plume dive at a given site. This section presents some common methods available, describes the data requirements for each method, provides a qualitative discussion of the uncertainty associated with the approach and data requirements, and presents some examples of how to apply the method.

Field Characterization

Risk-based decision-making can provide a framework for gauging the effort level required in a site investigation. Generally, the effort level for site characterization should be commensurate with the potential threat level to a receptor. At sites with a high level of threat to receptors, more extensive assessment of sources and exposure pathways is warranted. Prior to conducting field characterization tasks, available information about potential threats to receptors is used to select a preliminary level of characterization effort. As the potential threat (and corresponding level of characterization effort) increases, the need to evaluate the potential for significantly diving plume also increases, particularly if the consequences of missing a diving plume are great. Likewise, if the occurrence of a significantly diving plume is of great importance to identifying threat to receptors, then the effort expended on the characterization of the plume should increase. For example, if a supply well is located relatively close to a site and extracts groundwater from a deeper stratigraphic interval than the affected shallow aquifer, missing a diving plume may result in future impacts to the supply well. The flux of dissolved contaminant mass in a plume (total mass discharge) can be a useful metric for assessing threat to receptors (Einarson and Mackay 2001; Nichols and Roth 2004).

Guidance for evaluating the assessment level associated with various characterization tasks, such as vertical plume delineation, can be found in the technical bulletin "Strategies for Characterizing Subsurface Releases of Gasoline Containing MTBE" (API 2000). Although intended for characterizing MTBE releases, the principles can be applied to any contaminant investigation. In addition, several standards for site characterization are available from the American Society of Testing and Materials. The API technical bulletin outlines an approach for choosing between limited, standard, and detailed levels of site characterization. A limited assessment is characterized by relatively large sampling and/or monitoring well spacing, coupled with a review of regional hydrogeologic information, and a relatively low-resolution definition of the horizontal flow system. As the potential for adverse affects and resulting threats to receptors increases, an investigation may progress to a standard or detailed level of site characterization. A standard assessment may include closer sample and well spacing, and some degree of vertical plume and hydraulic property delineation. Detailed levels of assessments may include an evaluation of vertical flow potential, refined horizontal migration estimates, relatively dense sample and well spacing, and frequent use of depth-discrete monitoring points for more detailed horizontal and vertical delineation. Each level of assessment can be applied to the evaluation of the potential for and magnitude of plume dive and commensurate with the estimated potential threat to groundwater and/or surface water receptors.

If a detailed vertical characterization of the plume is warranted, a screening-level assessment of the potential for plume dive can be conducted using the analytical tools described below. Analytical tools can be used to guide installation of multi-level monitoring wells and well networks downgradient of the apparent leading edge of the plume, where typical depth-integrated monitoring wells may result in measured concentrations that appear to be reduced as a result of mixing of contaminant with the overlying accumulated clean water. Additionally, obtaining information about the general geology or depositional environment may assist with selecting well screened intervals for lithologic units that dip or otherwise influence the dip angle of a plume.

Depth-discrete monitoring points can confirm the presence of and measure the magnitude of vertical gradients at a site. The presence of a measured downward vertical gradient indicates a driving force is present for groundwater and plumes to migrate downward. Steep vertical or horizontal gradients can indicate regions where barriers to flow exist (such as major changes in lithology and hydraulic conductivity), where recharge rates are high, or where greater flow is induced as a result of pumping. An understanding of the site stratigraphy is useful when interpreting groundwater levels, gradients, and potential flow directions.

Direct-push technologies can be a cost-effective means for characterizing the subsurface lithology and the vertical and horizontal extent of a plume. Installation of multiple characterization points can be conducted in a relatively short time period and can initially define the plume and identify the number and location of permanent depth-discrete monitoring wells. Many ways to construct depth-discrete monitoring wells include individual completions of wells at different depths, completion of short screened wells within a single borehole, or a single well with multi-level ports or sampling chambers. Available guidance documents from state and federal agencies can assist in site characterization strategies and methods.

Biodegradation Characterization

Diving plume occurrence can be identified by analyzing depth-discrete shallow groundwater samples for dissolved oxygen, iron, methane, or other parameters that may indicate the presence of overlying unaffected groundwater versus groundwater affected by hydrocarbons or other contaminants. Clean recharge water will generally contain concentrations of dissolved oxygen greater than 1 milligram per liter (mg/l), iron concentrations less than 0.5 mg/l, and methane concentrations less than 0.1 mg/l. For hydrocarbon-affected groundwater, dissolved oxygen will be depleted and iron and methane concentrations will generally be above 1 mg/l. Depending on the age of the source, this electron-acceptor depleted "shadow" zone may extend downgradient of the current extent of the BTEX or MTBE plume. Detecting this zone can increase confidence that the monitoring network is located in the probable path of the plume. Dissolved organic carbon will also tend to be low (less than 2 mg/l) for unaffected water, and will be elevated (often above 10 mg/l) in hydrocarbon plumes (Weaver and Wilson 2000).

Care must be taken when collecting groundwater samples for dissolved oxygen analyses and other redox-sensitive species. Samples collected with bailers will be oxygenated and are not representative of groundwater geochemical conditions.

For contaminants that degrade in aerobic and/or anaerobic conditions, analyzing samples for the presence of daughter products will assist in identifying plume dive. For example, in aerobic geochemical conditions, MTBE has been known to degrade to tertiary-butyl alcohol (TBA). In these conditions, if a plume is diving, but downgradient portions include only TBA and not MTBE, sampling and analysis for MTBE only may falsely indicate the plume is not diving.

Analytical and Numerical Models

Ratio of Recharge Rate to Groundwater Discharge Rate

This approach is based on a conceptual model of vertical plume migration as a result of recharge accumulation at the water table. This approach assumes recharge is evenly distributed at the site, that the subsurface is homogeneous, the aquifer is thick relative to the accumulation of recharge, and that the rate of plume dive is uniform.

The slope of plume dive can be estimated by:

$$Slope = \frac{I}{V} = \frac{i}{q}$$

where

Slope = change in depth per change in horizontal distance, relative to the water table surface [ft/ft]

I = Accretion rate [ft/yr]; recharge rate divided by porosity, where the recharge rate is the net annual recharge to groundwater in feet/year

i = recharge rate [ft/yr]

V = horizontal groundwater seepage velocity [ft/yr]; the specific discharge divided by porosity

q = specific discharge, also known as Darcy velocity [ft/yr]

At a site in Cape Cod, multiple field investigations failed to adequately characterize a diving plume. Investigators used the above method to predict the extent of plume dive as a function of downgradient distance, and predicted a value of 1 foot of vertical migration of the plume per 100 feet of horizontal flow, which resulted in successful characterization of the diving plume over a distance of more than 13,000 feet (Reynolds et al. 1991).

The relationship of infiltration of areal recharge to groundwater seepage velocity can be used to estimate the potential for plumes to dive below a monitoring well screen. Plumes will completely dive below a monitoring well if the following relationship is satisfied (API 2000):

$$I \geq \frac{Vd}{x}$$

where

d = Lowest depth of monitoring well screen below the water table [ft]

x = Distance from source zone to the downgradient monitoring well [ft]

This relationship assumes uniform recharge and uniform velocity in the aquifer, and is strictly accurate only if the aquifer is infinitely thick, and the hydraulic gradient is insensitive to the rate of recharge. For aquifers that are bounded from below by a relatively impermeable aquitard, this relationship will tend to overestimate the rate of plume dive. More detailed methods that relax some of these simplifying assumptions are discussed below. In addition, this relationship does not address in-well dilution effects that may occur if the well screen intercepts a mixture of contaminated and uncontaminated groundwater.

For example, if the distance from a source to a downgradient monitoring well is 1,000 feet, and the downgradient monitoring well screen extends 10 feet below the water table, the recharge accretion would need to be greater than 1 percent of the ambient horizontal groundwater velocity for the plume to fully dive below the well screen, resulting in a false negative analytical result from the monitoring well. If the well were only 500 feet downgradient, the accretion rate would have to be greater than 2 percent of the recharge rate to produce a false negative result.

For the case where the well is 500 feet downgradient of the source, if the horizontal velocity were 100 feet per year, then the accretion rate would need to exceed 2 feet per year for the plume to dive below the monitoring well. Assuming a total porosity of 25 percent, this condition would require the net recharge exceed 6 inches per year.

Data requirements for this analysis include estimates of groundwater velocity, which is calculated from hydraulic conductivity, hydraulic gradient, and effective porosity. Hydraulic gradients can be calculated from monitoring well water level data, or in the absence of any site-specific data, they can be estimated from regional groundwater potentiometric maps (if available). Hydraulic conductivity can be estimated from published values based on lithologic type, or better, from site-specific information obtained from aquifer testing (Stallman 1971; Kruseman and DeRidder, 1991). Typically, porosity is estimated from published values based on lithologic types (Fetter 1988, USGS 1989).

Representative values for net recharge may be available from regional groundwater management authorities or regional groundwater studies. Many site-specific methods are available to estimate diffuse recharge from infiltration of precipitation (API, 1996). Often, recharge is expressed as a percentage of total annual rainfall accumulation. Values of 10 to 30 percent of total rainfall are common. Uncertainty exists with estimating recharge to groundwater due to infiltration of precipitation or other areal recharge processes. Consequently, recharge is often a calibration parameter in analytical or numerical models since it is usually a sensitive parameter for which little information is known.

Provided that the uncertainties are adequately considered, the ratio of recharge rate to groundwater discharge rate can provide a useful tool in preliminary evaluation of the potential for and approximate magnitude of plume dive, and can greatly enhance field characterization strategies.

Plume-Dive Calculator: Dupuit-Forcheimer One-dimensional Flow Solution

The U.S. EPA has developed a plume dive calculator available on OnSite, an On-line Site Assessment Tool resource website (U.S. EPA 2001) which is based on the Dupuit-Forcheimer one-dimensional solution for groundwater flow. The user enters upgradient and downgradient heads, a source and well location, and hydraulic conductivity and recharge for up to three segments of any length. Results include the plume depth at the well, and a drawing of the plume along the segments. An example is presented in Figure 6.

The solution determines the location of the phreatic surface for user-given boundary heads (aquifer thickness) or a downgradient head and hydraulic gradient, and then calculates streamlines based on the phreatic surface solution aquifer properties, and recharge rate. Groundwater velocities and travel times for retarded contaminants are also calculated with this method. Aquifer properties and the recharge rate are entered by the user and can be varied for up to three segments along the flowpath between boundary heads. Additional refinements to this on-line calculator are planned.

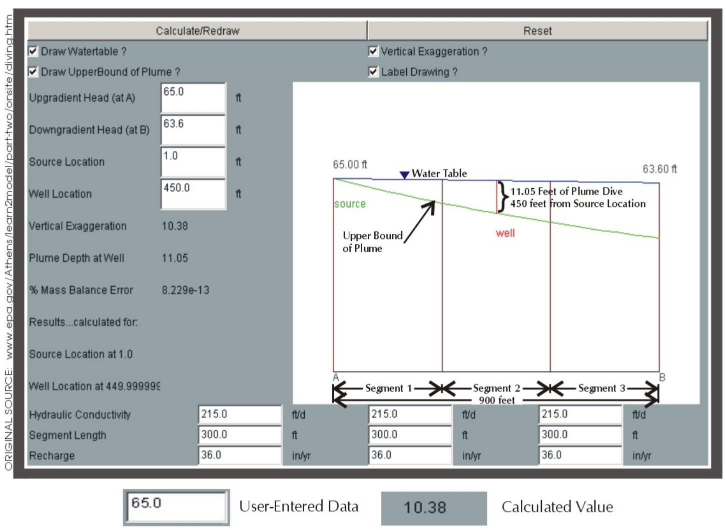

Figure 6. EPA Plume Dive Calculator

Uncertainty with the approach includes uncertainty associated with knowledge of the magnitude of hydraulic conductivity, hydraulic gradient, recharge, and aquifer thickness. Some uncertainty exists as a result of assuming these properties are uniform, even over a given segment. Collecting an adequate amount of lithologic or aquifer test data and using statistical evaluations to obtain representative values can reduce this uncertainty.

Supply Well Capture Analysis

Information regarding the location of supply wells relative to a site is an inexpensive, relative uncomplicated method for assessing the potential for plume dive. Many state and local water agencies or water purveyors have databases or websites where well locations, annual extraction rates, or estimated extent of well capture may be obtained. Capture zones can also be calculated using simple analytical equations (Todd 1980; Bear 1979), or if enough information is available, with numerical groundwater flow models. It is important to note that capture zones are three-dimensional, and may vary spatially as a function of subsurface heterogeneity or temporally with changing groundwater flow conditions and seasonal fluctuations in water demands and pumping. Methods to conceptualize and evaluate hydraulic capture zones are presented by Anderson and Woessner (1992) and Franke et al. (1998).

Numerical Flow and Transport Models

Many numerical models exist that will simulate the position of the phreatic surface, streamlines, and the three-dimensional distribution of a contaminant plume. The greater the desired resolution of spatial and temporal complexity in the system, the greater the data requirements. Required input parameters include groundwater flow velocity parameters, contaminant source release rates, and fate and transport parameters such as dispersion, retardation, and biodegradation rates. Numerical models can accommodate spatial variations in parameter values to represent more complex hydrogeologic conditions; however, the user should bear in mind that the accuracy of any model depends on the data and interpretations used to develop the conceptual model and to calibrate the computational model.

Model code selection depends on the objectives for a particular site. An example of a numerical model application is the East Patchogue, Long Island MTBE plume, where a numerical model (MODFLOW and MT3D) was created to enhance knowledge of plume movement, particularly in terms of the groundwater-surface water interactions at the site. The model included history matching to the observed plume distribution and was used to evaluate discharge to a lake and creek wetland. An analytical model (HSSM; Weaver et al. 1994) was used to calculate source terms for input to the numerical model. The calibrated flow and transport model was able to match observed MTBE concentrations at monitoring locations, and adequately simulated the observed plume dive behavior (Earle and Weaver 2002).

Many guidance documents, standards, and reference texts are available to assist in model selection, model development, calibration, sensitivity analysis, and documentation (U.S. EPA 1992; ASTM 2000; Spitz and Moreno 1996).

RECOMMENDATIONS

Many hydraulic and geologic factors contribute to the potential for plumes to dive. In addition, some biogeochemical conditions contribute to apparent plume dive, where the plume dive can appear greater than would otherwise be indicated by hydraulic or geologic factors. Table 1 presents a summary of these factors, indicates the conditions for these factors which will likely cause plume dive, outlines some characterization strategies, and qualifies some of the uncertainty associated with the strategies and methods.

For sites where a plume is likely to dive significantly, and the consequences associated with missing a diving plume are great, evaluating plume dive is an essential part of the development of a site conceptual model. The site conceptual model serves as the foundation for making site characterization decisions, evaluating risk to receptors, designing corrective actions, and assessing remedial performance. Understanding contaminant extent in general, and the potential for diving plumes in particular, can assist in making well-informed protective site management decisions.

Many of the methods described above, or a combination of those methods, can be used prior to and during field investigations to characterize the magnitude and extent of plume dive. Table 2 presents suggestions for a phased approach to evaluating the potential for plume dive at a site. To assess the potential for plume dive at a site and to avoid mis-characterizing a diving plume, consider the following steps as part of a risk-based site characterization strategy:

1. Evaluate potential threats to current and future groundwater and surface water receptors:
    - determine beneficial uses of groundwater and potentially affected surface water
    - determine density and proximity of supply wells, vertical separation between site and screened intervals, presence of impermeable units
    - evaluate the potential for impacted groundwater to discharge to surface water
2. Evaluate and/or Refine the Site Conceptual Model to assess whether hydraulic, geologic, or biogeochemical conditions at a site indicate the potential for plume dive:
    - identify site location relative to areas of potential recharge and discharge within the watershed;
    - identify nearby supply well locations, pumping rates, screened intervals, and assess the potential for wells to acts as vertical conduits;
    - assess the presence, direction, and magnitude of vertical gradients;
    - obtain information on site lithology – evaluate regional geology and local stratigraphy, identify lithologic types, likelihood of heterogeneity (preferential flow paths and/or trends in hydraulic conductivity with depth), evaluate if strata are dipping;
    - review available literature for nearby sites or sites with similar hydrogeologic conditions and assess the significance of diving plumes in those conditions.
3. If preliminary evaluation of site conditions indicates the potential for plume dive, estimate the degree of potential plume dive via application of the simple accretion rate relationship, the plume dive calculator, or other analytical calculations.
4. If analytical screening tools indicate plume dive may be significant, a more thorough or detailed analysis is warranted:
    - analytical and/or numerical models may guide or assist with monitoring well installation – locations and appropriate depths

- depth-discrete monitoring techniques can be used to characterize the horizontal and vertical extent of a plume, and evaluate the likely transport path of the plume
- geophysical methods can be used to identify the more permeable zones through which groundwater and solutes will preferentially flow

Numerical modeling can be a useful tool to assess plume dive if adequate site data is available and project objectives warrant the additional effort. It is likely the nature and extent of a plume, including the magnitude of historical plume dive would be defined prior to constructing a numerical model. In this case, a numerical model may be useful to predict the degree of dive under various future hydraulic conditions, such as variable recharge rates or groundwater-surface water interaction, or variations in supply well pumping. A well-characterized diving plume could serve as a calibration metric or target (Earle and Weaver 2002).

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Table 1—Summary of Diving Plume Characterization Methods and Applications

Factors Controlling Diving Plumes	Applications/Likely Conditions For Vertical Plume Migration	Characterization Strategy/Methods to Evaluate Potential for Diving Plumes	Method Uncertainty
Hydraulic			
Vertical gradients	Downward vertical gradients in recharge areas; upward vertical gradients in discharge areas	Measure heads in depth-discrete piezometers or monitoring wells	Typical uncertainty associated with field measurement error
Recharge	Location within a recharge area of regional groundwater flow system (groundwater divide in higher regions within the watershed, losing streams or river reaches) Presence of unpaved areas, or areas with potential for irrigation (agriculture, recreational) or sewer exfiltration Thin aquifers or low hydraulic conductivity aquifers where recharge would likely be a significant percentage of total groundwater flux	Ratio of recharge rate to specific discharge	Assignment of hydraulic conductivity, gradient, aquifer thickness, porosity Estimates of recharge rate Assumptions of uniform flow, uniform recharge over entire area or within discrete segments
		Plume Dive Calculator; Dupuit-Forcheimer solution	
		Numerical Modeling	Assignment of boundary conditions, hydraulic parameters, transport parameters; solution uniqueness; conceptual model uncertainty

Table 1—Summary of Diving Plume Characterization Methods and Applications (continued)

Factors Controlling Diving Plumes	Applications/Likely Conditions For Vertical Plume Migration	Characterization Strategy/Methods To Evaluate Potential For Diving Plumes	Method Uncertainty
Hydraulic (continued)			
Supply Wells	Areas where aquifer is used for supply purposes (municipal, industrial, agricultural) Locations with productive deeper aquifers Interconnectedness between aquifer with contaminant plume and supply well extraction intervals	Identify nearby supply well locations, screened intervals, presence of impermeable zones between the plume and the screened intervals, extraction rates, and capture zones Analytical tools for identifying well capture areas assume uniform flow conditions: WHPA and WhAEM are available from U.S. EPA: http://www.epa.gov/ada/csmos/models.html Calculations that determine the distance to the downgradient stagnation point, the shape of the outer capture zone streamlines, and the upgradient extent of capture as a function of time can be found in several hydrogeology textbooks (Bear 1979; Domenico and Schwartz 1990; Todd 1980).	Assignment of hydraulic conductivity, gradient, aquifer thickness, porosity Estimates of recharge rate Assumptions of uniform flow, uniform recharge over entire area or within discrete segments It may be difficult to obtain details regarding well locations, extraction rates, or extraction intervals

Table 1—Summary of Diving Plume Characterization Methods and Applications (continued)

Factors Controlling Diving Plumes	Applications/Likely Conditions For Vertical Plume Migration	Characterization Strategy/Methods To Evaluate Potential For Diving Plumes	Method Uncertainty
Hydraulic (continued)			
Evapotranspiration	Highly vegetated areas or areas with phreatophytes Shallow groundwater	Monitor water levels near dense tree stands or other phreatophytes	Typical uncertainty associated with field measurement error
Geologic			
Stratigraphy; Dipping Beds; Preferential Pathways	Geologic regions where dipping beds are likely; heterogeneous stratigraphic environments, layered material types Settings with significant interconnection between aquifers, increasing hydraulic conductivity with depth, presence of important flow zones or preferential pathways	Review regional geology and depositional environment 1. Review lithologic data from boring logs 2. Aquifer tests 3. Geophysical tests 4. Direct-push technology; cone penetrometer testing	Identification of material types included in boring logs from unknown sources is subjective and may be inaccurate Increase uncertainty for shorter-duration pumping tests; multiple depth-discrete tests may be required to assess conductivity profile with depth; slug tests and permeameter tests inexpensive but provide information over a small volume

Table 1—Summary of Diving Plume Characterization Methods and Applications (continued)

Factors Controlling Diving Plumes	Applications/Likely Conditions For Vertical Plume Migration	Characterization Strategy/Methods To Evaluate Potential For Diving Plumes	Method Uncertainty
Biogeochemical			
Biogeochemical Conditions	Presence of unpaved or drainage areas, leaky water mains, storm sewers or areas with potential for irrigation (agriculture, recreational) Shallow water table plume Commingling plumes (e.g., nearby landfill) Thin aquifers or low hydraulic conductivity aquifers where recharge would likely be a significant percentage of total groundwater flux	Profile geochemistry with depth; analyze water samples for geochemical indicators (dissolved oxygen, ferrous iron, methane, and other parameters) and for biodegradation products	Typical uncertainty associated with field measurement error, laboratory analysis, and reporting Uncertainty is reduced with increased use of depth-discrete sampling

Table 2—Suggestions for Evaluating the Potential for Plume Dive

1. Evaluate potential threat to current and future users of groundwater and/or surface water:		
Factor	**Component**	**Recommended Approach**
Potential Receptor Risk Factors	Identify current and future beneficial uses of groundwater and surface water	Review water agency reports and water resource management plans
	Identify nearby water supply wells	Review relevant water district, USGS, state and local government agency reports Assess density and proximity of supply wells, vertical separation between site and screened intervals, presence of impermeable units
Potential Migration Pathway Risk Factors	Consider impacted aquifers, and adjacent aquifers that may be impacted via horizontal or vertical migration	Obtain a thorough understanding of local and regional hydrogeology (see #1 above) Assess degree of communication between aquifer units (geology, hydrostratigraphy, vertical gradients)
	Evaluate the potential for impacted groundwater to discharge to surface water	Determine proximity to surface waters; review topographic maps and water agency reports; interpret groundwater and surface water elevations and flow directions

Table 2—Suggestions for Evaluating the Potential for Plume Dive (continued)

2. Evaluate the preliminary Site Conceptual Model to assess if site conditions indicate the potential for plume dive:		
Factor	**Component**	**Recommended Approach**
Geological Conditions	Depositional environment – assess if hydraulic conductivity increases with depth, or if there are other forms stratigraphic features that would have the potential to cause flow to increase with depth)	Review geologic reports and maps of the region Review boring logs Create hydrostratigraphic cross-sections parallel and perpendicular to dominant flow directions
	Dipping strata	
	Heterogeneity/preferential flow paths	
Hydraulic Conditions	Identify the location of the site relative to recharge and discharge areas	Review topographic maps to assess land surface features and locations of surface water bodies
	Assess if there are high recharge rates in conjunction with uncovered land surface	Compile precipitation data and land use maps
	Assess the presence of vertical hydraulic gradients - direction and magnitude Assess temporal variability in groundwater elevations and flow conditions	Review regional hydrogeologic reports – assess groundwater elevations within distinct hydrostratigraphic units

Table 2—Suggestions for Evaluating the Potential for Plume Dive (continued)

Factor	Component	Recommended Approach
Hydraulic Conditions (continued)	Identify the presence of nearby supply wells	Review locations and depths, pumping intervals, and integrity of construction Identify the presence or absence of low permeability units between the plume and pumping intervals Information may be found in regional hydrogeologic reports, from government agencies, or from water agencies
	Identify potential anthropogenic conditions – leaking water mains, irrigated fields, storm water conveyances, etc.	Review reports and information from local utility companies Review land use and zoning maps
Biogeochemical Conditions	Analyze samples for geochemical parameters indicative of the potential for biodegradation	Measure dissolved oxygen in the field with low-flow cells Measure parameters in the field or laboratory as appropriate If site-specific data do not exist, review regional hydrogeologic reports (government agencies, water agencies, etc.)

Table 2—Suggestions for Evaluating the Potential for Plume Dive (continued)

Factor	Component	Recommended Approach
Biogeochemical Conditions (continued)	Analyze samples for potential degradation products	Submit samples to laboratory for analysis If site-specific data do not exist, review regional hydrogeologic reports (government agencies, water agencies, etc.)
3. If evaluation of site conditions indicates the potential for plume dive to occur, and if threats to receptors are moderate to high, use analytical screening tools to plan and guide further site investigations:		
Tool or Method	**Purpose**	**Recommended Approach**
Ratio of Recharge Rate to Groundwater Discharge Rate	Assess potential slope of plume dive	Use site-specific estimates of hydraulic conductivity (single value or zones), calculate horizontal gradient from site groundwater elevations, estimate recharge rate(s) based on precipitation records from nearby station(s)
	Estimate potential recharge rates conducive to plume dive for given velocities and dive slopes	
	Estimate velocities conducive to plume dive for given recharge rates and angles of dive	
Capture Zone Analysis	Use simple or detailed analytical equations to calculate two-dimensional capture width and extent	WHPA and WhAEM are available at the U.S. EPA website: http://www.epa.gov/ada/csmos/models.html Calculations that determine the distance to the downgradient stagnation point, the shape of the outer capture zone streamlines, and the upgradient extent of capture as a function of time can be found in hydrogeology textbooks (e.g., Bear 1979, Domenico and Schwartz 1990, Todd 1980).

Table 2—Suggestions for Evaluating the Potential for Plume Dive (continued)

Tool or Method	Purpose	Recommended Approach
EPA Plume Dive Calculator - Dupuit-Forcheimer One-Dimensional Flow Solution	Calculate plume dive slope Estimate if plume is likely to dive below existing well screens or shallow well screens constructed with typical length (10 feet or greater)	http://www.epa.gov/athens/learn2model/part-two/onsite/diving.htm User enters up- and downgradient heads, hydraulic conductivity and recharge (single or three zones), and distance from a source to a downgradient well location
4. If evaluation of SCM, initial investigations, and analytical calculations indicate dive is likely and threat to receptors is moderate to high, conduct more detailed level of investigation:		
Greater Use of Depth-Discrete Monitoring Points	Improved horizontal and vertical plume delineation	Elevate level of assessment (e.g., limited to standard, standard to detailed) as appropriate Standard level of assessment – moderate sample spacing, some degree of vertical characterization, moderate use of depth-discrete sampling Detailed level of assessment – closer sample spacing, more extensive vertical characterization of concentrations and hydraulic properties, more extensive use of multi-level sampling
Numerical Modeling (optional)	More detailed (heterogeneous), site-specific, flow-balanced evaluation of groundwater flow system and solute migration and attenuation	Assess magnitude of plume dive or discharge to surface waters Guide choice of depth-discrete well locations and depths for more detailed site assessment

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