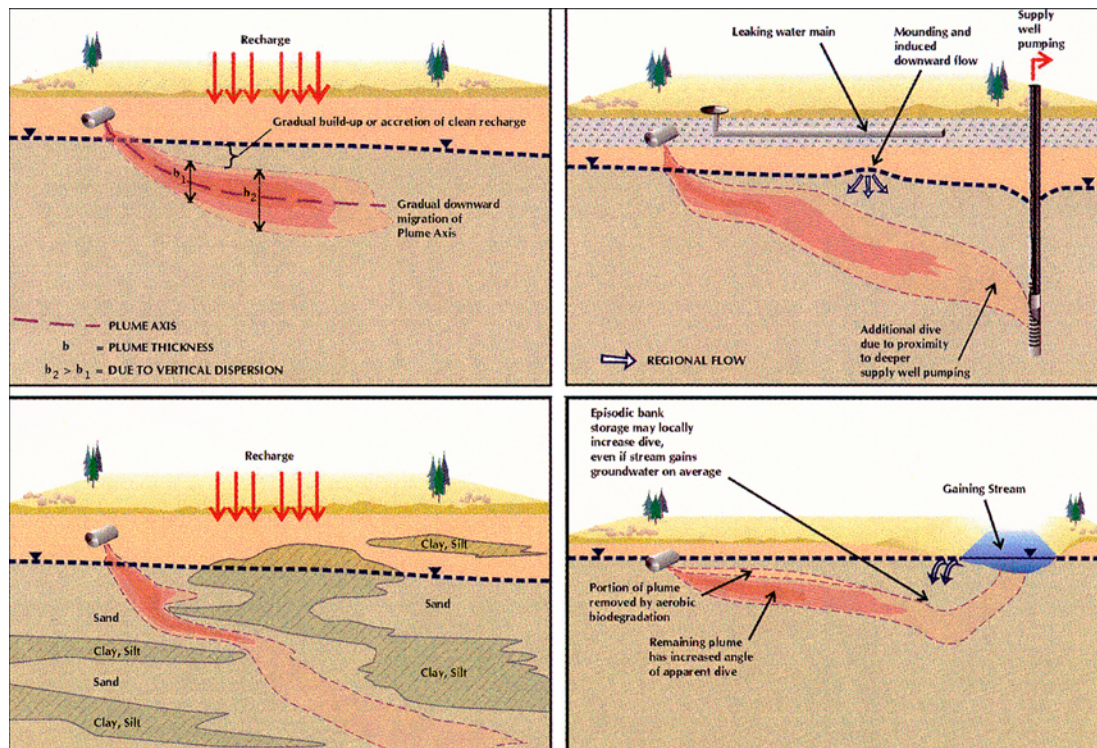


Downward Solute Plume Migration: Assessment, Significance, and Implications for Characterization and Monitoring of “Diving Plumes”

Regulatory Analysis and Scientific Affairs

API SOIL AND GROUNDWATER TECHNICAL TASK FORCE
BULLETIN 24
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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:

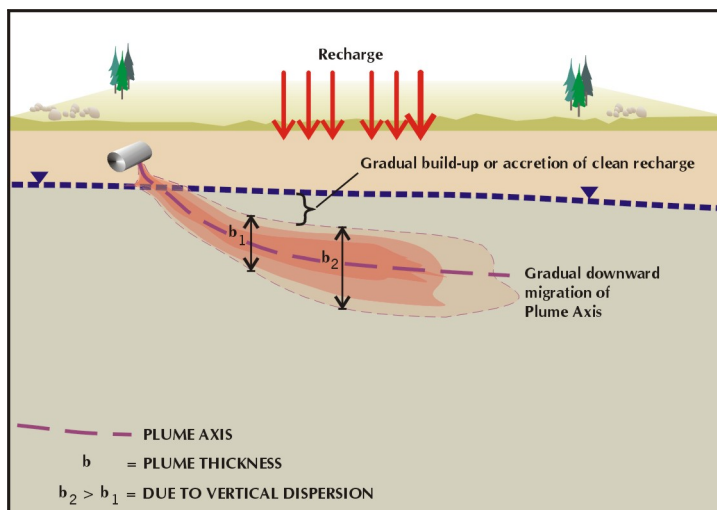


Figure 1. Example of a Diving Plume due to Accretion of Clean Recharge

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).

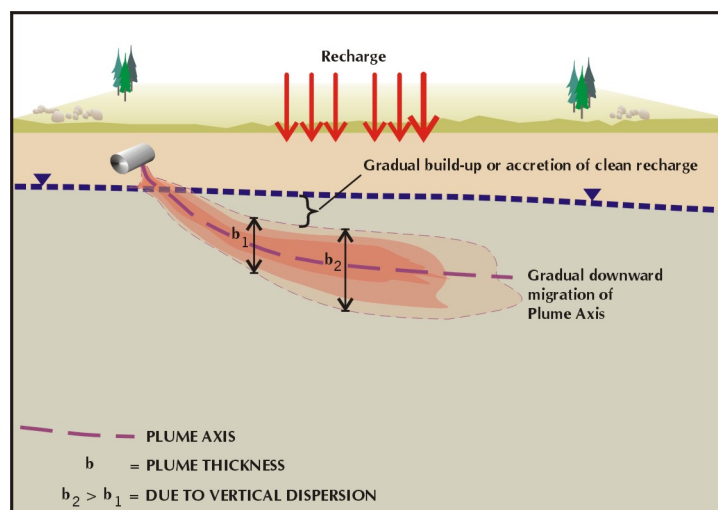


Figure 1. Example of a Diving Plume due to Accretion of Clean Recharge

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.