DOWNWARD SOLUTE PLUME MIGRATION: FACTORS THAT INCREASE THE SIGNIFICANCE OF PLUME DIVE

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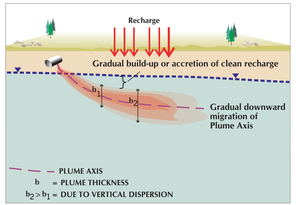


Example of a Diving Plume due to Accretion of Clean Recharge

WHAT IS "PLUME DIVE"?

The term "diving plume" refers to the gradual vertical migration of a dissolved-phase contaminant plume to greater depths within the subsurface with increasing flow path distance, resulting in the existence of a region of uncontaminated water overlying portions of a contaminant plume.

IMPLICATIONS TO MISSING A DIVING PLUME:

- Inadequate evaluation of risk to receptors
- Under-designing corrective actions
- Inadequate assessment of remedial performance

ABSTRACT

The term "diving plume" refers to the gradual vertical migration of a dissolved-phase contaminant plume to greater depths within the subsurface with increasing flow path distance, resulting in the existence of a region of uncontaminated water overlying portions of a contaminant plume.

The objective of this technical poster is to summarize issues related to the phenomenon of diving plumes. The factors that can cause plumes to dive are presented, and methods used to evaluate the potential for plumes to dive are outlined. Suggestions are provided regarding the identification and characterization of diving plumes.

Diving plumes have several implications for site characterization. If a diving plume is not adequately characterized, erroneous interpretations may occur concerning the risk to receptors, or to the significance of natural attenuation. Additionally, inadequate characterization poses a greater potential for under-designing corrective actions, and potentially inadequate assessment of remedial performance.

There are several hydraulic, geologic, and geochemical factors that contribute to plume dive. The major hydraulic factor is the existence of naturally occurring or anthropogenically induced vertical hydraulic gradients. Although a downward vertical gradient indicates the potential for a diving plume to occur, 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 rate of recharge and the groundwater seepage velocity.

Groundwater supply wells that extract groundwater at depth also induce downward vertical gradients, and can induce plume dive in the absence of effective confinement.

Geologic factors that influence vertical plume migration include variations in hydraulic conductivity with depth; strata orientation and dip angle; and heterogeneity within the aquifer.

Geochemical factors 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 due to accumulation of recharge. If the recharge water infiltrating into the subsurface contains greater amounts of dissolved oxygen, aerobic biodegradation may be enhanced near the water table.

There are several methods available to assess the potential for and characterize the magnitude of dive prior to detailed site 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 may dive below monitoring well screens for given distances. The U.S. Environmental Protection Agency (USEPA) 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 numerical models exist that will also simulate the position of the phreatic surface, streamlines, and the three-dimensional distribution of a contaminant plume.

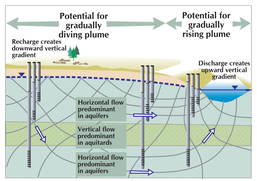
If site factors suggest a potential for significant dive, and the consequences of missing a diving plume are great, a relatively detailed vertical characterization of the plume may be necessary. Guidance for evaluating the level of assessment associated with various characterization tasks such as vertical plume delineation can be found in "Strategies for Characterizing Subsurface Releases of Gasoline Containing MTBE" (API 2000), which can be applied to any contaminant investigation. Analytical tools can be used a priori to guide installation of depth-discrete monitoring well networks near 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.

The occurrence of a diving plume may 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. Detecting such zones can increase confidence that the monitoring network is located in the probable path of the plume.

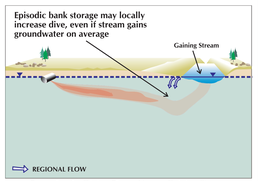
Many of the methods described above, or a combination of those methods, should be used prior to and during field investigations to characterize the magnitude and extent of contaminant plumes.

FACTORS CONTRIBUTING TO DIVING PLUMES:

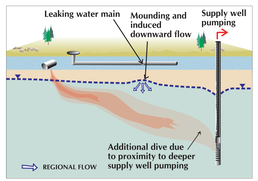
HYDRAULIC:



Expected groundwater flow conditions within a watershed that may lead to downward and/or upward solute plume migration

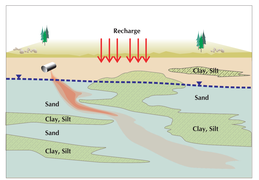


Example of a Diving Plume Near a Gaining Stream



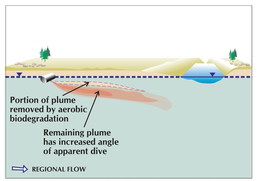
Example of a Diving Plume Along Leaking Water Main and Supply Wells

GEOLOGIC:



Example of a Diving Plume due to Stratigraphic Controls

GEOCHEMICAL:



Example of Apparent Dive Due to Geochemical Factors

THE PHENOMENON OF PLUME DIVING HAS BEEN OBSERVED AT SEVERAL DETAILED FIELD STUDIES THROUGHOUT THE UNITED STATES:

- **Long Island, New York** (Weaver and Wilson 2000; Weaver et al. 1999). Comparison of analytical results from depth-discrete monitoring wells to vertically averaged results indicated that the presence of clean recharge accreted above a plume led to a false portrayal of the contaminant distribution, including apparent shortening of plumes. At another Long Island site, downward migration of constituents was further induced by nearby supply well pumping from deeper aquifers.
- **South Carolina** (Landmeyer et al. 1998; Lahvis et al. 2003). 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 and possibly increased biodegradation in the shallow portions of the plume.
- **Cape Cod, Massachusetts** (Reynolds et al. 1991). Accretion of precipitation, rather than hydrodynamic dispersion, was the dominant factor controlling vertical migration of a VOC plume.
- **Kansas** (Hattan and Blackburn 1999). A shallow MTBE plume migrated downward along preferential pathways.
- **U.S. Naval Base Ventura County, Port Hueneme,** California (Amerson and Johnson 2003). A natural gradient tracer experiment on an MTBE plume indicated the plume center of mass deepened with migration distance due to the dip of the stratigraphy.
- The U.S. Environmental Protection Agency (USEPA) Region 5 is conducting 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).

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METHODS TO ASSESS POTENTIAL FOR AND MAGNITUDE OF DIVING PLUMES:

ANALYTICAL MODELS:

1.) Ratio of Recharge Rate to Groundwater Discharge Rate

This approach is based on a conceptual model of vertical plume migration resulting from accumulation of recharge at the water table. This approach assumes recharge is evenly distributed above the plume, 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:

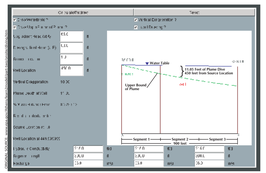
Slope = change in depth per change in horizontal distance, relative to the water table surface [ft/ft]
I = Accretion rate [ft/yr]; recharge rate divided by porosity, where the recharge rate is the net annual recharge to groundwater in feet/year
V = horizontal groundwater seepage velocity [ft/yr]; the specific discharge divided by porosity
i = recharge rate, [ft/yr]
q = specific discharge, also known as Darcy velocity [ft/yr]

2.) Capture Zone Analysis:

- Conceptualize and evaluate potential for downward migration due to heterogeneity and temporally changing flow conditions
- Obtain information regarding well locations, extraction intervals and rates, and estimated capture areas from local water agencies or water purveyors
- Use simple analytical equations to calculate 2-dimensional capture width and extent (Todd 1980; Bear 1979)
- Use more detailed methods to conceptualize and evaluate hydraulic capture zones (Anderson and Woessner 1992; Franke et al. 1998)

3.) Dupuit-Forcheimer 1-D Solution

- Flow properties homogenous over specified regions
- Uniform recharge over specified regions
- Specified heads at upgradient and downgradient extent of region of interest



EPA Plume Dive Calculator
http://www.epa.gov/athens/learn2model/part-two/onsite/diving.htm

NUMERICAL MODELS:

- Simulate the position of the phreatic surface, flowlines, and 3-dimensional plume distribution
- Can accommodate spatial variations in parameters to represent more complex conditions
- Data requirements are commensurate with the site conceptual model and the desired model spatial and temporal complexity
- Selection of model code depends on project objectives
- East Patchogue, Long Island Site - MODFLOW and MT3D were used to evaluate plume movement and groundwater/surface water interaction; the model adequately simulated the observed plume dive (Earle and Weaver 2002)

FIELD CHARACTERIZATION:

- Details of characterization techniques can be found in ASTM standards and several guidance documents such as API's "Strategies for Characterizing Subsurface Releases of Gasoline Containing MTBE" (API Publication 4699, February 2000).
- Level of effort should be commensurate with the risk to receptors; i.e., evaluate the need to characterize a diving plume before conducting a detailed field characterization.
- If detailed field investigation is warranted, use analytical tools to guide installation of multi-level monitoring networks.
- Obtain information on geology, stratigraphy, and depositional environment to guide selection of screened intervals.
- Depth-discrete monitoring can be used to confirm the presence or absence of vertical hydraulic gradients, which can indicate the potential for plumes to dive at a given site.
- Use geochemical and/or isotopic characterization to assess if clean water overlies a contaminant plume.

RECOMMENDATIONS TO EVALUATE IF A SITE HAS THE POTENTIAL FOR PLUME DIVE:

Many of the methods described above, or a combination of those methods, should be used prior to and during field investigations to characterize the magnitude and extent of contaminant plumes. To assess the potential for significant plume dive to occur at a site, and to avoid mis-characterizing a diving plume, initial characterization tasks should include the following elements:

1.) Assess whether hydraulic, geologic, or geochemical conditions at a site indicate the potential for plume dive to occur:

- 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 significance 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 occurences of plume dive at nearby sites or sites with similar hydrogeologic conditions.

2.) If preliminary evaluation of site conditions indicates the potential for plume dive to occur, estimate the degree of potential plume dive via application of the simple accretion rate relationship, the plume dive calculator, or other analytical calculations.

3.) 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.