Regulatory Framework

Introduction

- Groundwater quality and protection has become highly regulated in last two decades.
- While peripheral to the science of hydrogeology, legal aspects essentially define the course of an investigation.
- Legal and regulatory issues are covered and updated by books and seminars on regular basis.
- Refer to these sources, U.S. Code of Federal Regulations, and state and local regulations for specific case-by-case applications.

Water Rights

- Protect the property aspects of groundwater.
- Correlative rights, English rule are rights of capture. Referred to as law of biggest pump. Reasonable and beneficial use. Water can be exported. Transfer of right with transfer of land.
- Apportioned rights, American rule. Right established by use and application to governing agency. transfer of right independent of transfer of land.
- Mutual prescription. Right administered by prescription during low supply periods.
- Pueblo rights.

Federal Law

- National Environmental protection Act of 1970.
- Federal Water Pollution Control Act of 1972.
- Toxic Substances Control Act of 1976.
- Resource Conservation and Recovery Act of 1976.
- Clean Water Act of 1977.
- Surface Mining Control and Reclamation Act of 1977.
- Safe Drinking Water Act of 1979.
- Comprehensive Environmental Response, Compensation, and Liability Act of 1980.
- Hazardous and Solid Waste Amendments of 1984.
- Superfund Amendments and Re-authorization Act of 1986.

No federal groundwater protection statute!
Federal guidelines protect groundwater under drinking water (usually).

Groundwater quality categories:

- I - Special groundwater
- II - Groundwater currently and potentially a source of drinking water.
- III - Groundwater not a source of drinking water.

Drinking water is considered highest beneficial use of groundwater resource.

Resource Conservation and Recovery Act (RCRA)

- Intent is to provide "cradle to grave" regulation of hazardous waste.
- Modeled after Solid Waste Disposal Act of 1965.
- Important for hydrogeology: CFR 40, Part 264, Sub-part F.
- Outlines geologic information for protection of aquifers near hazardous waste disposal sites.

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

- Superfund created to identify sites contaminated by release of hazardous materials and finance remediation by "responsible parties", state or federal funds.

Underground Storage Tank (UST) Programs

- Different scale from CERCLA and RCRA.

EPA UST Program

- 40 CFR, Parts 280 and 281.
- Nationwide regulation of underground storage tanks.
- Overflow and corrosion protection, soil and groundwater monitoring, notification of agencies.

State and Local UST regulations

- Similar in scope and usually modeled after federal program.

Communications with Regulatory Agencies

- Crucial to success of investigation.
- Agencies do not have answers to specific questions -- most laws are guidance regulations and subject to interpretation.

Groundwater Geochemistry-Basics

Introduction

- Naturally occuring groundwater has a geochemical variability caused by natural processes.
- Flow of water, formation type, annual fluctuations, and groundwater mixing.
- Changes also imparted due to leakage.
- Baseline chemistry crucial.
- Water moving vertically from surface will affect groundwater chemistry.
- Analytical techniques change as regulatory standards change.
- Changes in standards are directly reflected in cost of cleanup.

Inorganic Composition and Quality

- Inorganic chemistry deals with physical and chemical factors that govern groundwater movement.
- Quick, inexpensive chemical information to allow groundwater classification.

Electrical Conductivity

- Ability of substance to conduct electrical current
- Roughly proportional to total concentration of ionic species in solution.

pH

- Measure of concentration of dissolved protons. Low pH is acid, high pH is basic.
- $pH = -\log([H+])$
- Unstable parameter and is measured in the field.

Oxidation-Reduction

- Relative intensity of oxidizing or reducing conditions in solutions.
- Correlated with dissolved oxygen

TDS

- Measure of total solids in water after drying of a sample.

Characteristic	Principal Cause	Significance	Remarks
ardness	Calcium and magnesium dissolved in the water	Calcium and magnesium combine with soap to form an insoluble precipitate (curd) and thus hamper the formation of a lather. Hardness also affects the suitability of water for use in the textile and paper industries and certain others and in steam boilers and water heaters.	USGS classification of hardness (mg/L as $CaCO_2$): 0–60: Soft 61–120: Moderately hard 121–180: Hard More than 180: Very hard
H (or ydrogen-ion ctivity)	Dissociation of water molecules and of acids and bases dissolved in water	The pH of water is a measure of its reactive characteristics. Low values of pH, particularly below pH 4, indicate a corrosive water that will tend to dissolve metals and other substances that it contacts. High values of pH, particularly above pH 8.5, indicate an alkaline water that, on heating, will tend to form scale. The pH significantly affects the treatment and use of water.	pH values: less than 7, water is acidic; value of 7, water is neutral; more than 7, water is basic
pecific lectrical onductance	Substances that form ions when dissolved in water	Most substances dissolved in water dissociate into ions that can conduct an electrical current. Consequently, specific electrical conductance is a valuable indicator of the amount of material dissolved in water. The larger the conductance, the more mineralized the water.	Conductance values indicate the electrical conductivity, in micromhos, of 1 cm^3 of water at a temperature of 25°C.
Total dissolved solids	Mineral substances dissolved in water	Total dissolved solids is a measure of the total amount of minerals dissolved in water and is, therefore, a very useful parameter in the evaluation of water quality. Water containing less than 500 mg/L is preferred for domestic use and for many industrial processes.	USGS classification of water based on dissolved solids (mg/L): Less than 1,000: Fresh 1,000–3,000: Slightly saline 3,000–10,000: Moderately saline 10,000–35,000: Very saline More than 35,000: Briny

Source: Heath (1982).

Types of Organic Contaminants

- Volatile organic compounds: Compounds with low vapor pressure. May include solvents, fuels with aromatic chemistry. May include halogenated aromatics. Miscibility and solubility varies, but generally low.
- Acid-base neutral compounds: may include polynuclear aromatics, ethers, esters, phenols, PCBs, plasticizers, etc.
- Agricultural chemicals: pesticides, herbicides, nematocides, and related chemicals.
- Trace elements: Heavy metals, asbestos, and cyanides.
- Alcohols and ketones: Cleaners, highly mobile due to high solubility.
- Oils, greases, petroleum products: Hydrocarbons used for lubricants and fuels. Wide range of solubilities although generally immiscible.

Data Analysis and Report

- Site maps
- Cross sections
- Groundwater elevation contour maps
- Groundwater contamination contour maps.
- Data tables.
- Narrative

Using Previous Reports

- Do so with care -- may contain a wealth of information or be misleading.
- Archive copies of references used so they can be produced upon demand.

Hydrogeological Assessment (for Flow and Transport)

A) Geologic framework
- Previous reports
- Geophysical techniques

B) Developing the geology
- Geologic maps
  - Areal distribution
  - Lithologic types
  - Thickness
  - Stratigraphy
  - Structural Features
- Topographic maps
- Structure-contour maps
- Depth maps
- Thickness maps
- Soil maps
- Texture maps
- Water-level contour maps
- Flow-net maps and sections
- Hydrogeologic sections
- Fence diagrams

C) Developing the hydrology
- Precipitation
- Infiltration
- Irrigation
- Streamflow

D) Preparing illustrations

From: Well Investigation Program Manual
AB 1803, July 1989
California Water Resources Control Board

Hydrogeologic Assessment Reports

THE PORTER-COLOGNE WATER QUALITY CONTROL ACT

And Related Code Sections (Including 1988 Amendments)

January 1989

California State Water Resources Control Board

25208.8. A person who receives a notice from a regional board, pursuant to Section 25208.7, or who files an application for an exemption pursuant to Section 25208.5 or 25208.13, shall submit a hydrogeological assessment report to the regional board. A qualified person shall be responsible for the preparation of the report and shall certify its completeness and accuracy. The report shall contain, for each surface impoundment, any information required by the state board or the regional board, and all of the following information:

(a) A description of the surface impoundment, including its physical characteristics, its age, the presence or absence of a liner, a description of the liner, the liner's compatibility with the hazardous wastes discharged to the impoundment, and the design specifications of the impoundment.

(b) A description of the volume and concentration of hazardous waste constituents placed in the surface impoundment, based on a representative chemical analysis of the specific hazardous waste type and accounting for variance in hazardous waste constituents over time.

(c) A map showing the distances, within the facility, to the nearest surface water bodies and springs, and the distances, within one mile from the facility's perimeter, to the nearest surface water bodies and springs.

(d) Tabular data for each surface water body and spring shown on the map specified in subdivision (c) which indicate its flow and a representative water analysis. The report shall include an evaluation and characterization of seasonal changes and, if substantive changes result from season to season, the tabular data shall reflect these seasonal changes.

(e) A map showing the location of all wells within the facility and the locations of all wells within one mile of the facility's perimeter. The report shall include, for each well, a description of the present use of the well, a representative water analysis from the well, and, when possible, the water well driller's report or well log.

(f) An analysis of the vertical and lateral extent of the perched water and water-bearing strata which could be affected by leachate from the surface impoundment, and the confining beds under and adjacent to the surface impoundment. This analysis shall include all of the following:

(1) Maps showing contours of equal elevation of the water surface for perched water, unconfined water, and confined groundwater required to be analyzed by this subdivision.

(2) An estimate of the groundwater flow, direction of the perched water, and all water-bearing strata on both the maps and the subsurface geologic cross sections.

(3) An estimate of the transmissivity, permeability, and storage coefficient for each perched zone of water and water-bearing strata identified on the maps specified in paragraph (1).

(4) A determination of the rate of groundwater flow.

(5) A determination of the water quality of each zone of the water-bearing strata and perched water which is identified on the maps specified in paragraph (1) and which is under, or adjacent to, the facility. This determination shall be conducted by taking samples either from upgradient of the surface impoundment or from another location which has not been affected by leakage from the surface impoundment.

(g) An indication as to whether the groundwater is contiguous with regional bodies of groundwater and the depth measured to the groundwater, including the depth measured to perched water and water-bearing strata identified on the maps specified in paragraph (1).

(h) The following climatological information:

(1) A map showing the contours for the mean annual long-term precipitation for the surrounding region within 10 miles of the surface impoundment.

(2) Calculations estimating the maximum 24-hour precipitation and maximum and minimum annual precipitation at the facility based upon direct measurement at the facility or upon measured values of precipitation from a nearby climatologically similar station.

(3) The projected volume and pattern of runoff for any streams which, in a 100-year interval, could effect the facility, including peak stream discharges associated with storm conditions.

(i) A description of the composition of the vadose zone beneath the surface impoundment. This description shall include a chemical and hydrogeological characterization of both the consolidated and unconsolidated rock material underlying the surface impoundment, and an analysis for pollutants, including those constituents discharged into the surface impoundment. This description shall also include soil moisture readings from a representative number of points around the surface impoundment's perimeter and at the maximum depth of the surface impoundment. If the regional board determines that the use of suction type soil sampling devices are infeasible due to climate, soil hydraulics, or, soil texture, the regional board may authorize the use of alternative devices. The report shall arrange all monitoring data in a tabular form so that the data, the constituents, and the concentrations are readily discernible.

(j) A measurement of the chemical characteristics of the soil made by collecting a soil sample upgradient from the impoundment or from an area which has not been affected by seepage from the surface impoundment and which is in a hydrogeologic environment similar to the surface impoundment. The measurement shall be analyzed for the same pollutants analyzed pursuant to subdivision (i).

(k) A description of the existing monitoring being conducted to detect leachate, including vadose zone monitoring, the number and positioning of the monitoring wells, the monitoring wells' distances from the surface impoundment, the monitoring wells' design data, the monitoring wells' installation, the monitoring development procedures, the sampling methodology, the sampling frequency, the chemical constituents analyzed, and the analytical methodology. The design data of the monitoring wells shall include the monitoring wells' depth, the monitoring wells' diameters, the monitoring wells' casing materials, the perforated intervals within the well, the size of the perforations, the gradation of the filter pack, and the extent of the wells' annular seals.

(*l*) Documentation demonstrating that the monitoring system and methods used at the facility can detect any seepage before the hazardous waste constituents enter the waters of the state. This documentation shall include, but is not limited to, substantiation of each of the following:

(1) The monitor wells are located close enough to the surface impoundment to identify lateral and vertical migration of any constituents discharged to the impoundment.

(2) The monitoring wells are not located within the influence of any adjacent pumping wells which might impair their effectiveness.

(3) The monitor wells are only screened in the aquifer to be monitored.

(4) The chosen casing material does not interfere with, or react to, the potential contaminants of major concern at the facility.

(5) The casing diameter allows an adequate amount of water to be removed during sampling and allows full development of the monitor well.

(6) The annular seal prevents pollutants from migrating down the monitor well.

(7) The methods of water sample collection require that the sample is collected after at least five well volumes have been removed from the well and that the samples are transported and handled in accordance with the United States Geological Survey's "National Handbook of Recommended Methods for Water-Data Acquisition," which provides guidelines for collection and analysis of groundwater samples for selected unstable constituents. If the wells are low-yield wells, in that the wells are incapable of yielding three well volumes during a 24-hour period, the methods of water sample collection shall insure that a representative sample is obtained from the well.

(8) The hazardous waste constituents selected for analysis are specific to the facility, taking into account the chemical composition of hazardous wastes previously placed in the surface impoundment. The monitoring data shall be arranged in tabular form so that the date, the constituents, and the concentrations are readily discernible.

(9) The frequency of monitoring is sufficient to give timely warning of leachate so that remedial action can be taken prior to any adverse changes in the quality of the groundwater.

(10) A written statement from the qualified person preparing the report indicating whether any constituents have migrated into the vadose zone, surface water bodies, perched water, or water-bearing strata.

(11) A written statement from the qualified person preparing the report indicating whether any migration of leachate into the vadose zone, surface water bodies, perched water, or water-bearing strata is likely or not likely to occur within five years, and any evidence supporting that statement.

(Added by Stats. 1984, Ch. 1543; amended by Stats. 1986, Ch. 260, Stats. 1987, Ch. 748.)

Remediation and Cleanup

Conceptual Approach

- Site remediation must consider limits of technical expertise, regulations, environmental protection desired, and economics.
- How clean is clean?
- The answer to this question will determine the level of effort and budget for any remediation.

Techniques

"Pump-and-Treat" technologies:

- Air Stripping volatilizes contaminants in groundwater pumped from the subsurface.
- Effective for solvents and fuels -- requires air permits.
- Carbon Bed Adsorption captures contaminants in pumped groundwater.
- Expensive depending on how often carbon canisters must be regenerated.

Other Technologies:

- Excavation is physical removal of contaminated materials for disposal at a suitable disposal site.
- Excavation of hazardous materials is costly, and cost of transportation and disposal is a significant portion of the overall cost.
- Postexcavation sampling and testing are required to determine the effectiveness of cleanup.
- Incineration is thermal destruction of contaminants into innocuous compounds.
- Rotary kiln, liquid injection, multiple hearth, and fluidized beds are used.
- Bioremediation treatment uses techniques borrowed from sewage treatment technology.
- Has been used for treating excavated soils contaminated with petroleum fuels.
- In-situ bioremediation recirculates contaminated water with an electron source and nutrients to stimulate natural subsurface degradation.
- Site geology dependent.

- Soil Vapor Venting vents vapors of volatile contaminants from the unsaturated zone.
- Passive venting of excavated soils is relatively inexpensive -- air permits.
- Active venting forces air through soils by blowers and vacuum pumps.
- Soil properties important.
- Air permits required.

Interim Cleanup

- Interim cleanup begins before investigation is complete.
- An example is separate phase removal of light immiscible contaminants.

Final Cleanup and Closure

- Final allowable concentrations based on health risk.
- Post cleanup reporting to determine effectiveness on cleanup.

Final demarkation of the area to be remediated, the so-called zero contamination line. Failure to locate the edge of cleanup, and agree to that boundary with the regulators, may result in additional investigation and cleanup. Additional hydrogeology and engineering costs may arise following the initial site investigation, to collect more information if the assessment is incomplete.

Acceptance of the cleanup plan by the regulating agencies (with public review if required). This will involve complete negotiation of contamination extent, cleanup methods, cleanup costs, and selected cleanup technology and related engineering design. Resolving these issues may take years and may require substantial changes in the technical approach (even possibly new investigations).

Securing the needed permits from the appropriate agencies. This may include excavation, equipment and well construction, waste discharge methodologies, and permits.

Preparation and review of the site safety plan and personnel medical monitoring as required.

Determination of the costs of cleanup. This varies depending on the remediation method and can include budgets for cleanup, maintenance, monitoring, and site closure. Cleanup costs are typically high, easily reaching the tens or hundreds of thousands of dollars (not including future monitoring or other efforts). Usually a cost analysis is included in a cleanup plan when the most cost-effective remedial option is determined. Cost may change due to inflation, additional equipment needs, additional review by regulators, effectiveness of the initial cleanup, or changes in subsurface conditions not anticipated in the site investigation.

Selection of the cleanup contractor, usually by competitive bid. The bid proposal would include the cleanup plan and documentation so that the contractor will perform the work in a cost-effective manner and negotiate additional funds for unforeseen contingencies or problems.

Finalization of any physical plant or containment facilities, including design engineering and drawings, work timetables, safety plan, and other site procedural documents.

Setting up the decontamination area for field work, or constructing and installing the needed treatment, monitoring, and safety equipment (including the calibrating and adjusting equipment, long-term maintenance, etc.).

1. Background history
   - cause and location of contaminant release
   - how release was detected
   - estimate of duration and volume of release
   - type of leak detection system installed at site
2. Site characterization
   - subsurface exploration and soil sampling methods
   - groundwater monitoring well design
   - groundwater sampling methods, water level measurements
   - sampling protocol (e.g., analytical chemical lab, chain-of-custody documentation, sampling preservation)
   - regulatory requirements for analyses performed
   - methods used to detect and measure separate-phase product
3. Extent of soil and groundwater pollution
   - vertical and lateral extent of subsurface contamination
   - number and location of exploratory borings
   - number and location of monitoring wells
   - definition of separation-phase product
   - definition of dissolved contaminants
4. Hydrogeology
   - subsurface lithologies, primary and secondary permeability
   - aquifer characteristics
   - aquifer and aquitard relationships
   - groundwater flow direction and gradient
   - seasonal and diurnal groundwater elevation changes
   - geologic cross sections
   - preferred contaminant pathways
   - permeability characteristics of the vadose zone
5. Beneficial uses of groundwater
   - existing and future groundwater uses
   - regional basin plan requirements
   - potential receptor/risk assessment
6. Remedial action
   - interim remedial actions used
   - development of remedial alternatives
   - screening remedial alternatives/technology/engineering
   - rationale for selected remedial action
   - soil remediation method (e.g., excavation, vapor venting)
   - groundwater remediation method
   - potential/existing impact of remedial action(s)
7. Effectiveness of remediation
   - consistency of cleanup levels with federal/state guidelines
   - verification monitoring program
   - potential impacts from residual contamination
8. Site closure
   - closure plan reviewed by lead agency
   - verification monitoring data reviewed
   - "sign-off" (no further work required)

Investigation Goals

- Define site geology and stratigraphy
- Define hydrogeology
- Collect soil samples for vertical and horizontal vadose contamination delineation.
- Collect groundwater samples to define plume extent.
- Adjust sampling program as data indicates.

Plume Location and Delineation

Plume Delineation

Typical work plan consists of five steps.

(1) Source delineation.

(2) Detection monitoring.

(3) Plume length determination.

(4) Plume width determination.

(5) Plume thickness determination.

Source Delineation

- Locate source(s) of groundwater contamination:
  - abandoned wells
  - underground tanks
  - underground pipelines
  - abandoned lagoons

- Define lateral and vertical extent of associated groundwater contamination:
  - soil borings
  - soil recovery probes
  - geophysical methods (TDR, GPR etc.)

- Characterize chemical properties of contaminants:
  - species
  - density
  - solubility in water
  - sorption characteristics
  - reaction characteristics

- Select indicator parameters.

Detection Monitoring

·Drill adjacent to source zone to define site geology (Penetrometers may be a viable alternative to drilling).

·Identify upper-most aquifer.

·Install at least 3 monitoring wells in source area to determine local groundwater flow direction and magnitude (hydraulic gradient)

·Compare downgradient indicator parameters to background well (or an upgradient well) to detect contamination.

·Conduct aquifer tests to determine aquifer hydraulic characteristics.

slug tests
pumping tests
tracer tests

Plume length

·Locate monitoring wells to define longitudinal plume dimension.

·**Use Darcy's law to estimate plume length for siting delineation monitoring wells.**

hydraulic gradient
aquifer porosity (effective)
age of source

·Estimate dispersivity as 10% of plume length estimate if dispersive estimates are required for well siting.

·Site downgradient wells according to these estimates. Try to site one well beyond expected plume length to serve as a no-detect location.

·Measure water levels in delineation wells, collect and analyze groundwater samples at each well.

·Update geologic site maps and groundwater elevation maps.

·Repeat as needed to define plume length.

Plume Width

- Locate wells on a transverse line to define plume width.
  Use 1/3 to 1/2 plume length as estimate if needed.

- Measure water levels, collect and analyze groundwater samples at each well.

- Plumes ideally will have a teardrop or elliptic shape.

- Length-width ratio depends on:
  - aquifer physical characteristics
  - seepage velocity
  - dispersive effects
  - anisotropy and inhomogeneity

Plume Thickness

- Install multi-level cluster wells, or multi-level samplers etc. to determine depth of contaminant penetration within aquifer.

- Evaluate potential hydraulic communication with deeper aquifers.
  - vertical leakage rates
  - vertical fracture networks
  - abandoned boreholes
  - vertical fault systems

- Define lateral and vertical plume boundaries and interior contaminant levels.

References

U.S. Environmental Protection Agency, Office of Solid Waste, 1986. RCRA Ground-Water Monitoring Technical Enforcement Guidance Document, OSWER-9950.1

PLUME DELINEATION

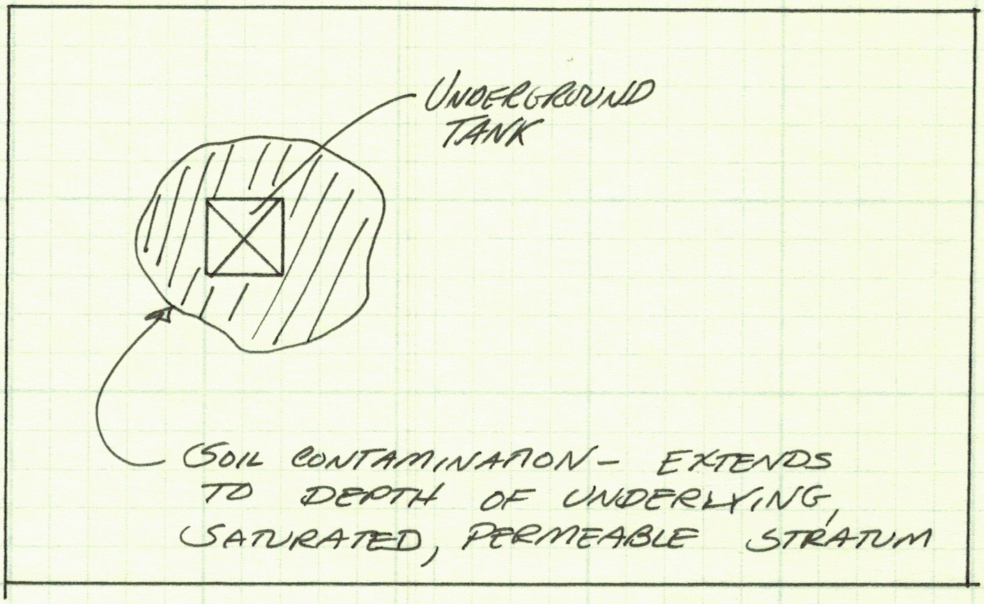


FIGURE 1. SOURCE DELINEATION

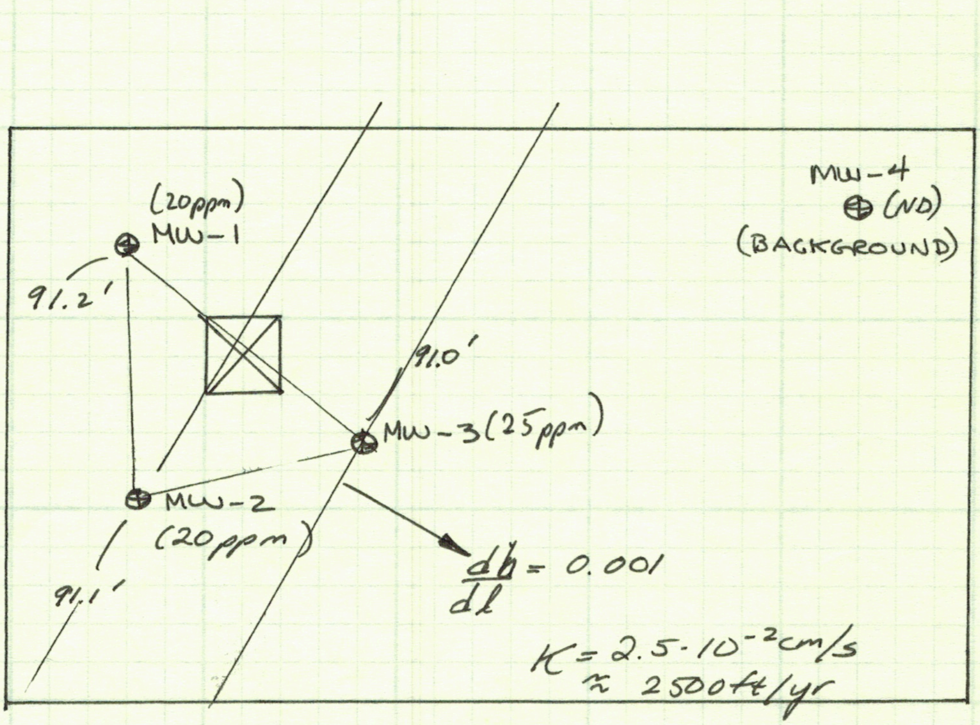


FIGURE 2. DETECTION MONITORING

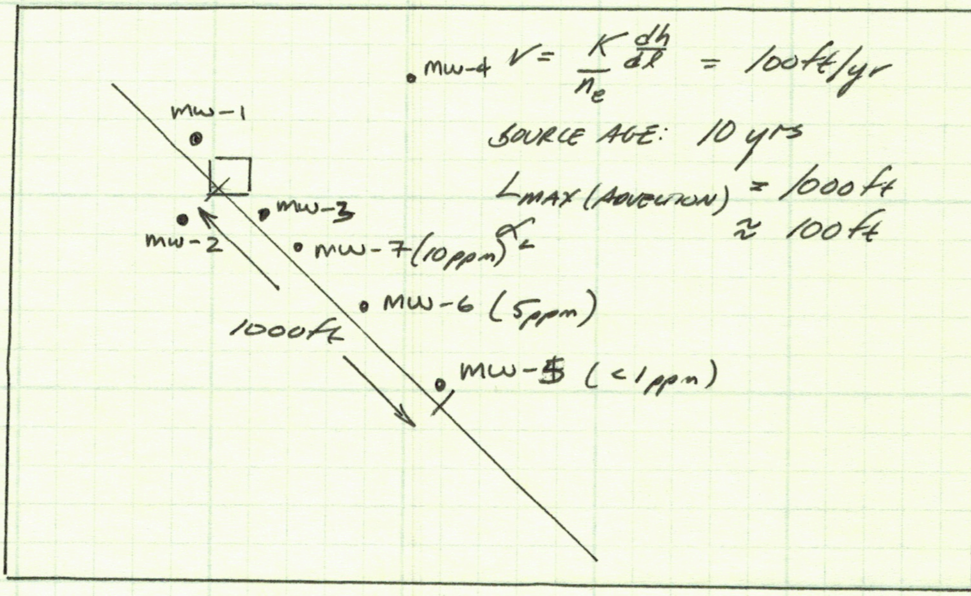


FIGURE 3. PLUME LENGTH

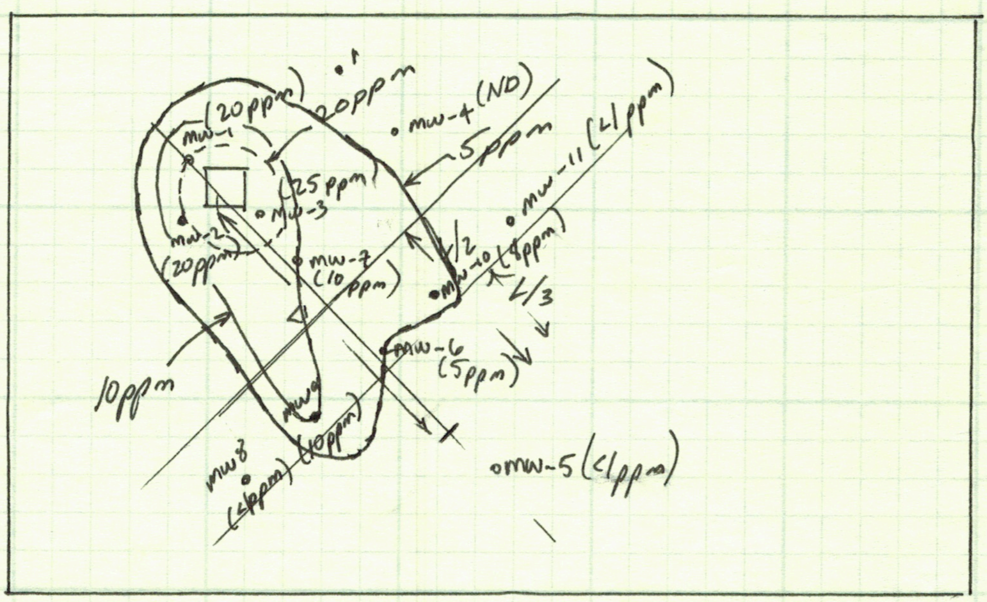


FIGURE 4. PLUME WIDTH

PLUME DELINEATION

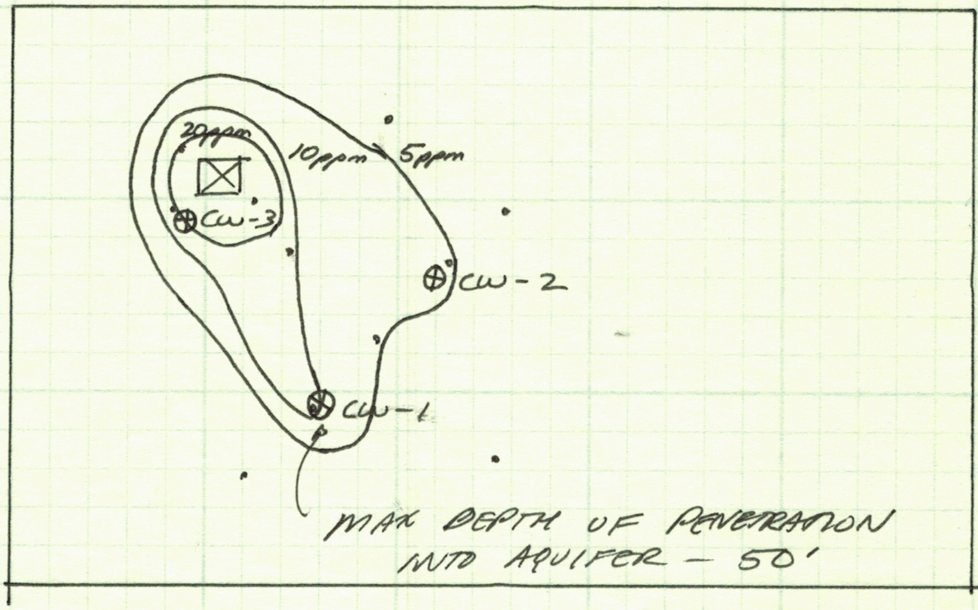


FIGURE 5a. PLUME THICKNESS

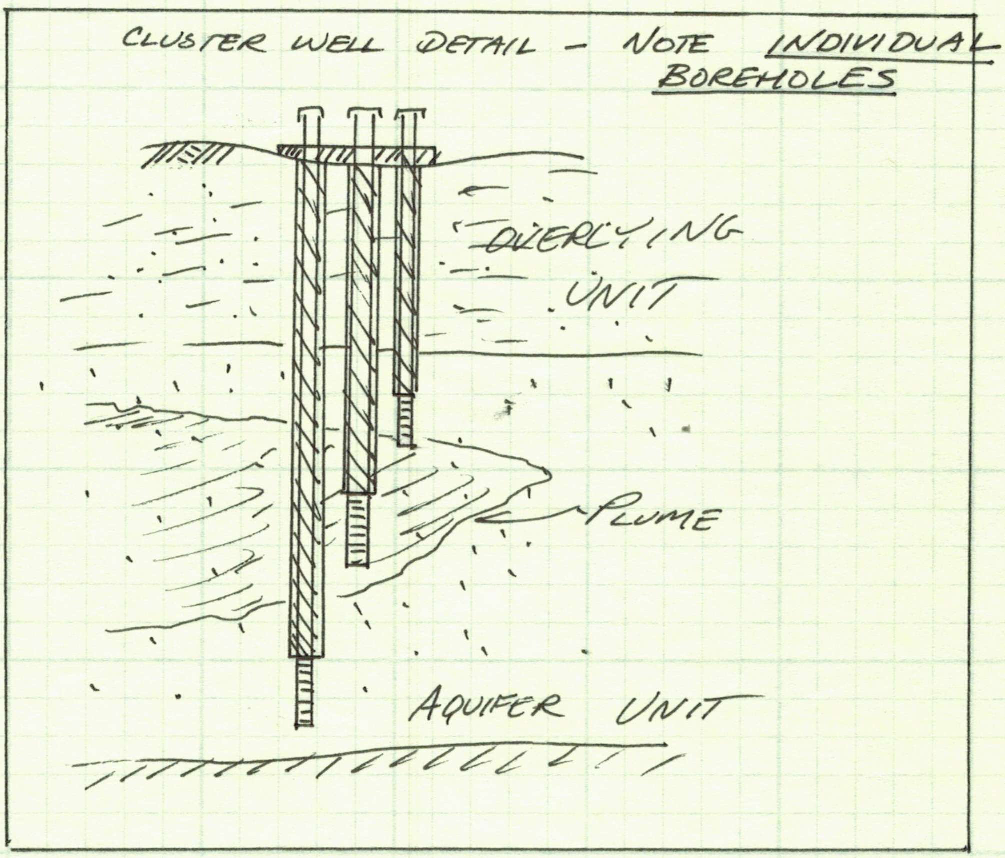
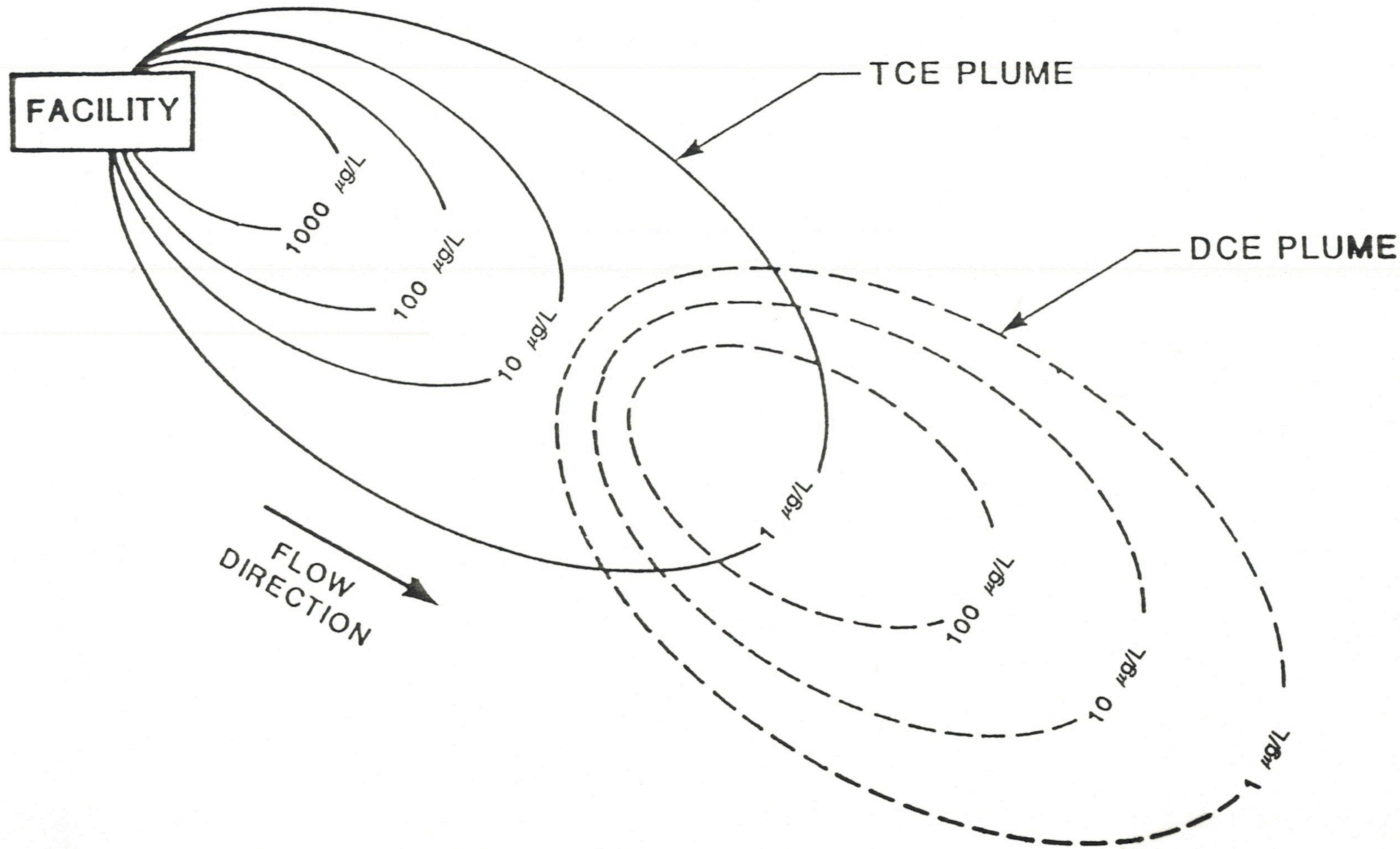
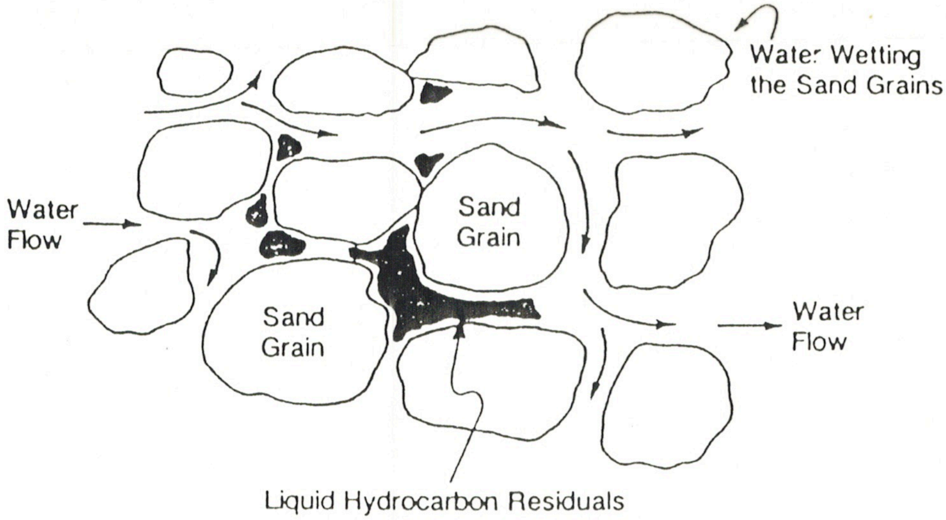
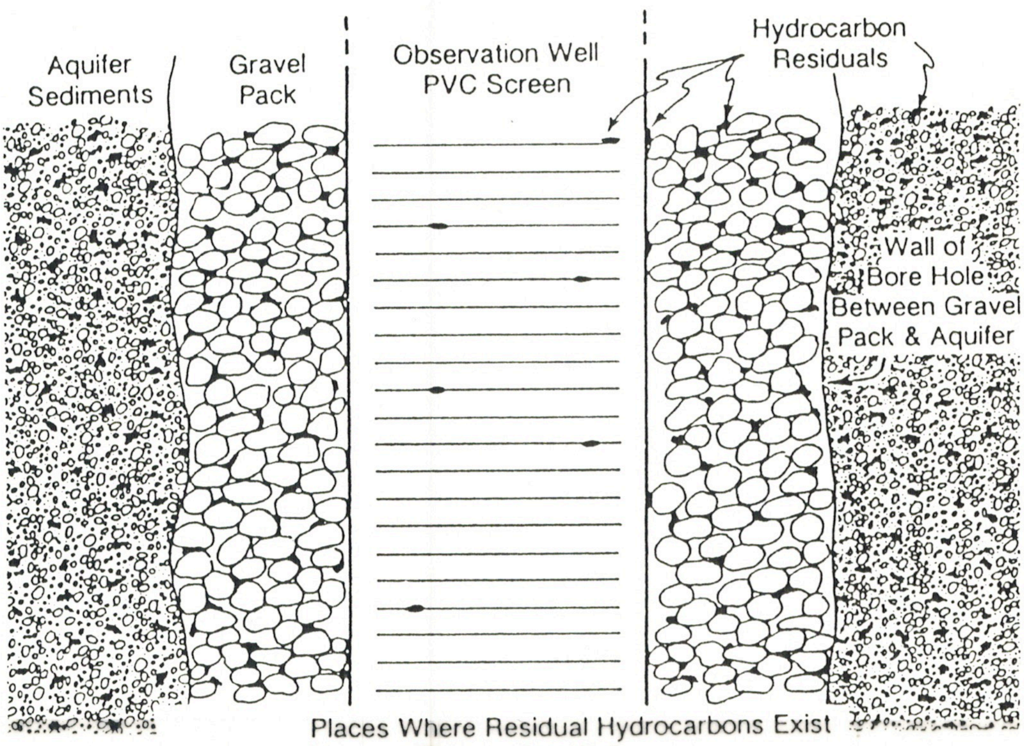


FIGURE 5b. CLUSTER WELL DETAIL

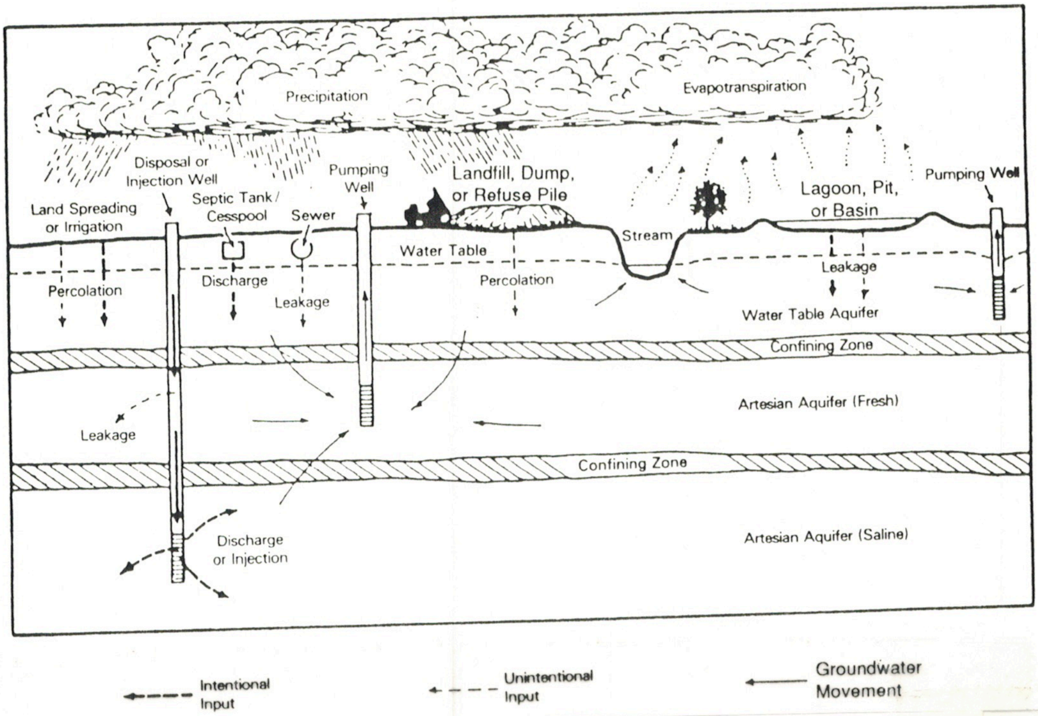

FACILITY
TCE PLUME
DCE PLUME
1000 μg/L
100 μg/L
10 μg/L
1 μg/L
100 μg/L
10 μg/L
1 μg/L
FLOW DIRECTION

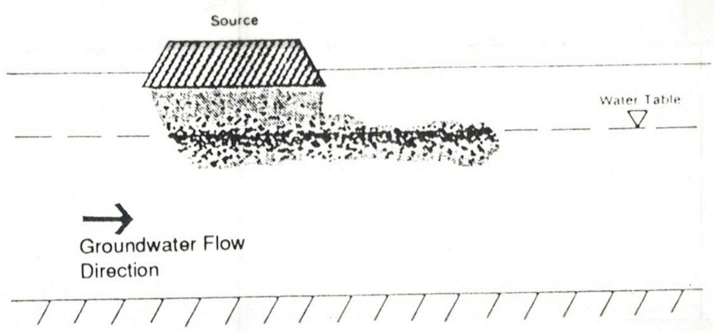


Liquid Hydrocarbon Residuals Trapped In Water-Wet Sand Grains.

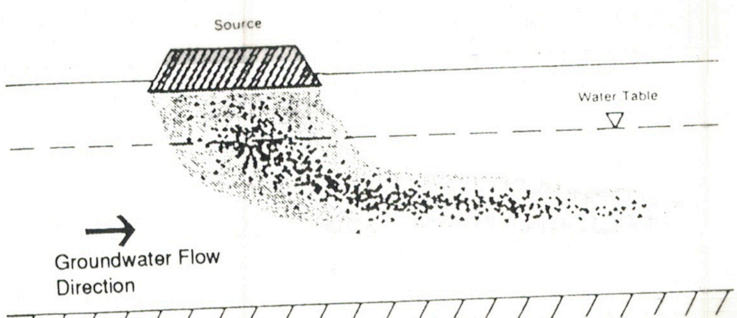


Places Where Residual Hydrocarbons Exist Near an Observation Well

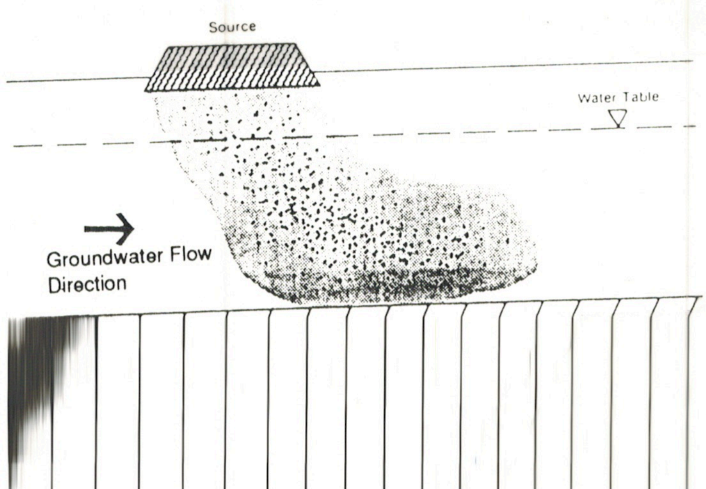




CONTAMINANT LESS DENSE THAN GROUNDWATER



CONTAMINANT DENSITY SAME AS GROUNDWATER



Laboratories

- Contract laboratories usually perform analyses using recognized standards.
- Some constituents may not have "standard" methods.

Selection Criteria

- Quality assurance and quality control using spike samples, duplicates, specific standards to ensure accuracy and precision of chemical analyses.
- Site sample matrix taken into account when interpreting data.
- Units of concentration consistency from report to report.
- Detection limits explained and clearly indicated.

Data Reporting and Detection Limits

- Accuracy of instruments is critical.
- Extreme care in interpreting data near detection limits.

Data Management

- Computers and database software useful for managing huge quantities of data generated.
- Data management should be planned prior to initiation of investigation.
- Provisions for modification of management methods should also be considered.

Contaminant Pathways

Introduction

- Migrates through unsaturated zone to aquifer.
- Background conditions crucial to determine if pre-release conditions already violate standards.

Sources and Types of Contaminants

- Municipal: sewers, sanitary landfills, disposal wells, military bases.
- Industrial: manufacture, subsurface tanks, pipelines, mines, oil fields.
- Agricultural: fertilizers,pesticides, wastes, irrigation return flow.
- Other: transport spills, material stockpiles, septic tanks, testing labs.

Contaminant Properties

- Solubility, vapor pressure, partition coefficient, sorption/desorption.
- Oxidation-reduction behavior, hydrolysis, halogenation/dehalogenation, photochemical breakdown.

Contaminant Pathways in Unsaturated Zone

- Follow fluid migration pathways.
- Fractures and macropores influence behavior.
- Cracked clay, even with very small fractures can transport materials downward quickly.
- Vapor flow can be significant -- vapors can recondense.
- Vapor surveys useful, quick, and inexpensive to help define suspected sources of contamination.
- Residual contamination.

Contaminant Movement in Saturated Zone

- Follows groundwater flow.
- Dispersion may be significant, but ability to predict flow paths is extremely useful and considered more important.

Plume Configuration and Movement

- Advection is transport by bulk motion of groundwater. Darcy's law.
- Dispersion is transport by spreading due to molecular effects and braided flow pathways. Fick's law used as working assumption.
- Plumes are teardrop or elliptical shaped, with long axis aligned in direction of groundwater flow.
- Densities of contaminants affect transport -- floaters and sinkers.
- Contaminants change over time, may decay to less or more toxic compounds.

Aquifer Stratigraphy Effects

- Chromatographic effects due to different contaminant and aquifer properties. Different constituents in same aquifer migrate at different speeds.

Movement in Fractured Rock

- Motion along fracture traces and within blocks.

Movement By Leakage Between Aquifers

- Aquitards may enhance or retard vertical motion of contaminants, while retarding vertical motion of water.