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DEPARTMENT OF
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Ground Water Plume Containment and Management Annotated Bibliography

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INTRODUCTION

The following bibliography was created to assist engineers, hydrogeologists, environmentalists, etc. in obtaining literature on ground water plume containment and management technologies. The scope of this short summary is to be used to get a flavor of the subjects that are discussed in the literature contained in the bibliography. It briefly touches on most of the subjects associated with ground water plume containment and management, but does not discuss this information in any great detail.

A wide range of literature from very short journal articles to long in-depth technical documents are contained in the bibliography. The following is a list of the areas searched while gathering the literature: Washington State Library (including library loans from other libraries), Environmental Protection Agency (EPA) Region 10 Library, Washington State Department of Ecology Library, EPA Hazardous Waste Database, Ground Water On-Line Database, Environment Index/Abstracts Annuals (and other journal indexes), the large bibliography from "state-of-the-art of aquifer restoration." (123), and the databases which the reference desk at the Washington State Library searched for Ecology - Biosis Previews, Compendex Plus, Enviroline, Pollution Abstracts, Aquatic Science Abstracts, CAB Abstracts, Cris USDA, Ca. Search, Fluidex, Water Resources Abstracts, and Waternet. Additional literature can be found using the Environment Index/Abstracts Annuals, Journal Indexes and other available databases.

This bibliography is presented with this introduction first, followed by a brief summary of the information contained in the literature, and then the alphabetical listings of the literature on plume containment and management. The bibliography, in most cases, contains the location of where the piece of literature can be found. In citations where there is no location, the literature was privately owned when it was reviewed. In this case, the Washington State Library may be able to get this literature for you or tell you where it can be obtained. The Ecology Library is listed numerous times as the library holding literature. However, this literature (especially EPA documents) can, in most cases, also be obtained from the Washington State Library or the EPA Region 10 Library in Seattle.

Finally, the citations that are used in this summary direct the reader to some (not all) of the literature discussing that particular subject cited. The literature titles are generally indicative of the subjects discussed in the texts. Some of the more informative pieces of literature (generally longer and more in depth) include 4, 11, 24, 26, 36, 37, 115, 116 and 123. These citations are rarely referenced in the summary but would be a good place to search if those that are referenced do not provide sufficient information, or a general overview of plume containment and management is desired.

FIGURES

Acronyms

EPA	Environmental Protection Agency
GPM	Gallons per Minute
HWICP	Hazardous Waste Investigations and Cleanup Program
AWWA	American Water Works Association
ILL	Inter Library Loan
ASCE	American Society of Civil Engineers
NWWA	National Water Well Association

PLUME CONTAINMENT AND MANAGEMENT

An integral part of remedial action where contamination has migrated in the ground water is plume containment and management. This report examines four major categories of plume containment and management technologies. These are ground water pumping/recharge, subsurface drains, low permeability barriers, and a brief discussion of innovative technologies. A general description of these major types is included here, but the reader should keep in mind that in all of these main categories there are numerous variations to each technology.

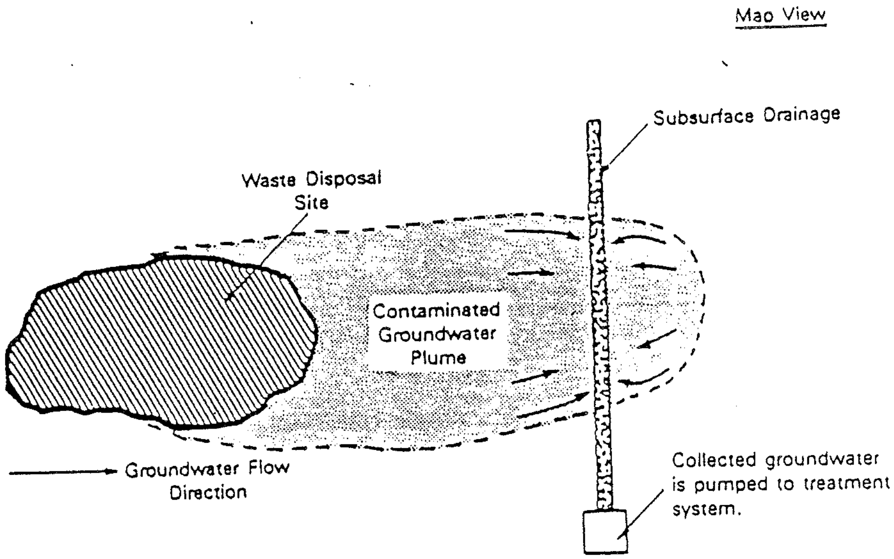
The technology most frequently employed is ground water pumping/recharge. This technology relies on the alteration of the direction of leachate plume movement (alters the natural hydraulic gradient) by the extraction or injection of ground water through wells. A cone of depression (extraction) or a cone of impression (injection) is formed to control or remove the plume. Extraction and injection wells can be used in combination or on a stand alone basis for plume control.

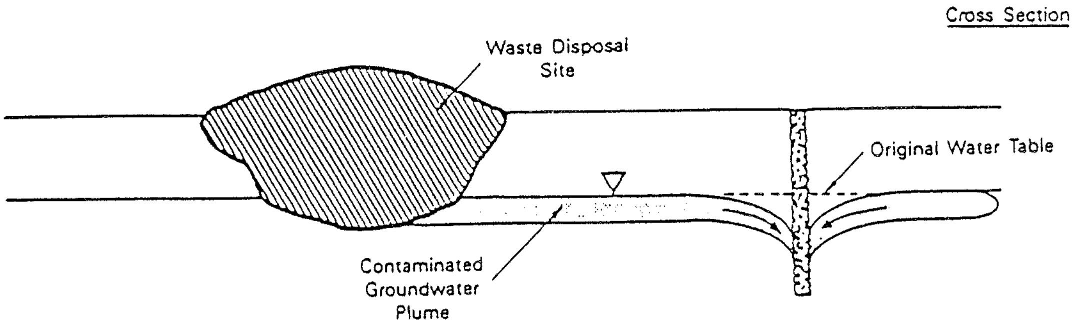
A technology that is similar to ground water pumping is that of subsurface drains. These are permeable drains placed in the subsurface to intercept leachate plumes. Water flows into the permeable drains where it can be pumped from the subsurface for treatment or recharge (see Figure 1).

Low permeability barriers are placed in the subsurface to redirect ground water flow around a contaminated site or to contain ground water contamination within a site. This technology is not used to remove leachate plumes but to manage them by redirecting ground water flow or by lowering the ground water table (when used with other ground water removal technologies (i.e., pumping)) to avoid ground water and waste contact, (see Figure 2) or to contain them by completely surrounding a waste site or plume (see Figure 3). Low permeability barriers are often combined with pumping/recharge to obtain optimum hydrodynamic control.

(Figure 1)

THE USE OF SUBSURFACE DRAINAGE TO CONTAIN A LEACHATE PLUME

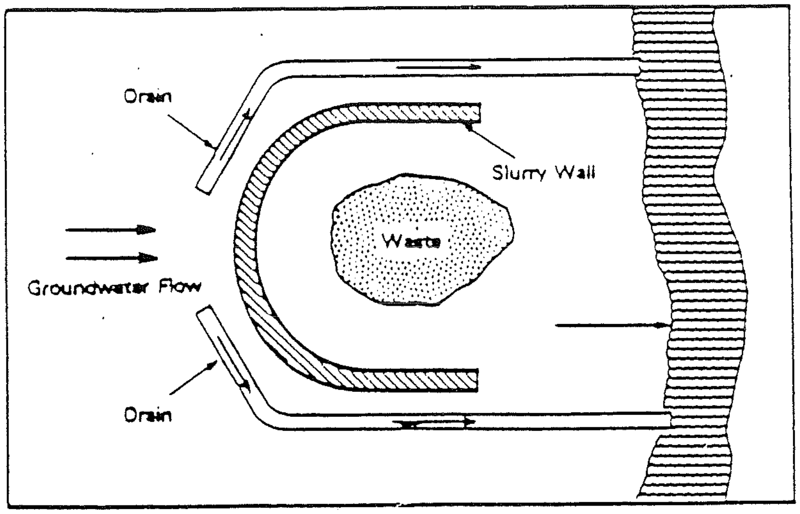




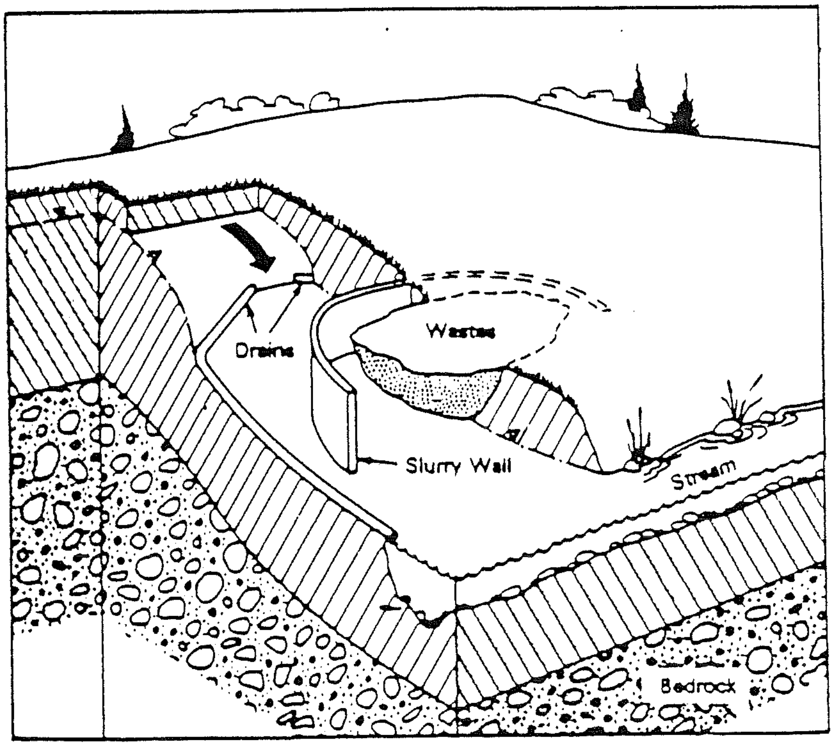
["Leachate Plume Management" 1985 by Edward Repa and Charles Kufs (37)]

(Figure 2)

PLAN OF UPGRADIENT PLACEMENT WITH DRAIN



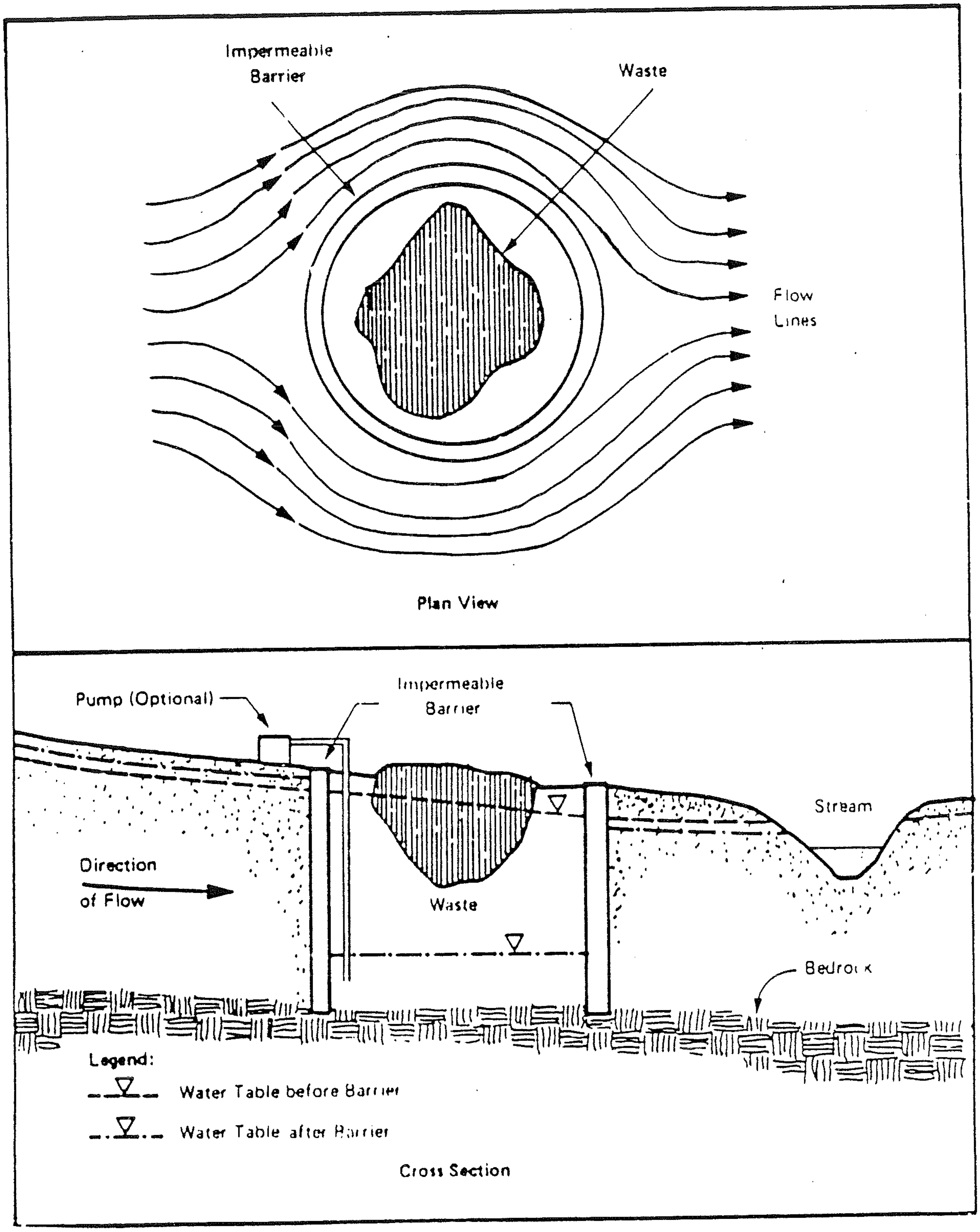
CUT-AWAY CROSS-SECTION OF UPGRADIENT PLACEMENT WITH DRAIN



[(Spooner et al, 1984) As Cited by Edward Repa and Charles Kufs (37)]

(Figure 3)

EFFECT ON GROUNDWATER LEVEL OF BARRIER SURROUNDING WASTE



["Handbook for Evaluating Remedial Action Technology Plans" 1983 by John Ehrenfeld and Jeffrey Bass (26)]

Innovative technologies are newer technologies such as permeable treatment beds, in-situ biological and chemical treatment, and block displacement. These technologies are not well tested but could possibly become viable alternatives as plume containment technologies or management strategies.

All of the four technologies can be used alone or in combination with other containment technologies to achieve design objectives. When selecting a containment and/or management technology for remediation several variables must be considered, including the availability of the technology, type of contamination, constructability of the system, capital cost, operation and maintenance cost, space limitations, volume of contaminants, length of time the contaminant has been in the subsurface, hydrologic conditions, geologic conditions, extent and dimensions of plume, potential and/or immediate hazards imposed by the contaminant, length of time required to clean up to desired cleanliness, health and environmental benefits, other technologies being used to remediate the situation, and other site specific variables.

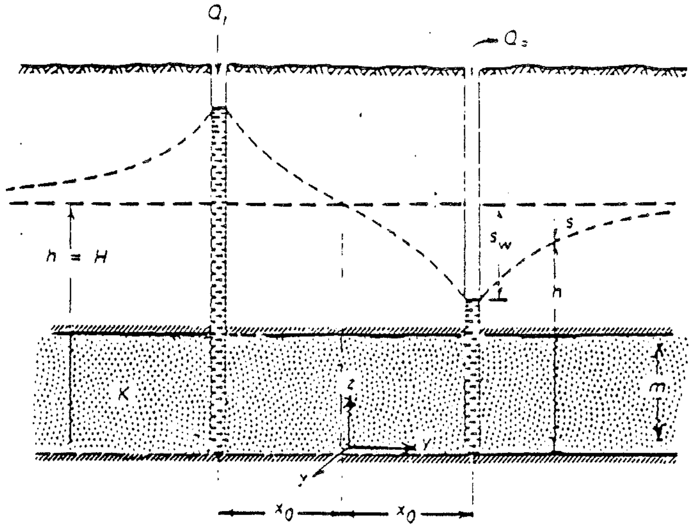
There are books written about the design and construction considerations for each of the four main containment technologies. Therefore, the following discussion on design and construction parameters very briefly covers only the major parameters discussed throughout the literature. The basic conceptual design considerations for plume containment can be extrapolated from literature, but a site specific investigation will be needed to collect necessary data to complete the design.

Ground Water Pumping and Recharge

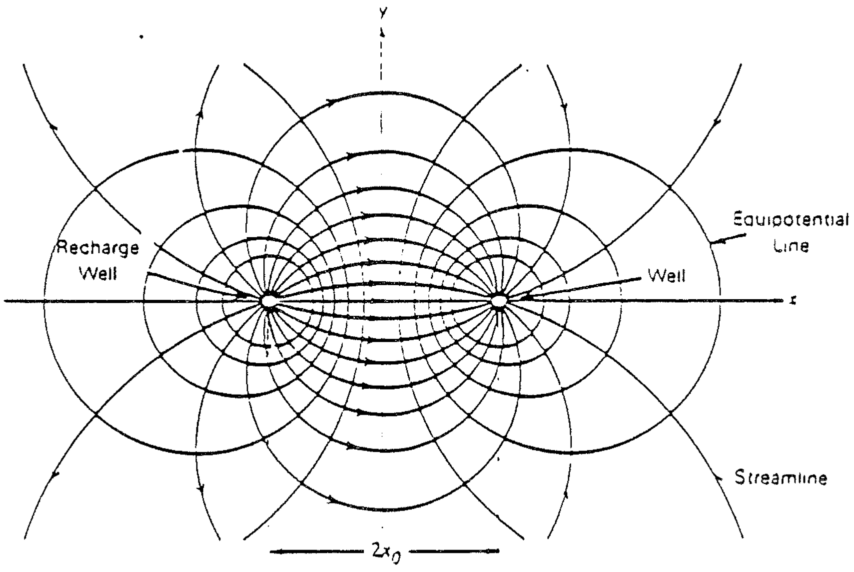
Ground water pumping/recharge is a containment technology that has been used in many sites and is fairly well documented. With ground water pumping, cones of depression (extraction) or cones of impression (injection) are created to contain and/or remove contaminated plumes (see Figure 4). This type of hydrodynamic control may stop contamination at the source by lowering the water table below the waste (see Figure 5). It can also be used to alter the velocity of the plume and/or it's direction (see Figure 6). A

(Figure 4)

RECHARGE AND DISCHARGE WELLS IN A CONFINED AQUIFER



Cross-sectional View

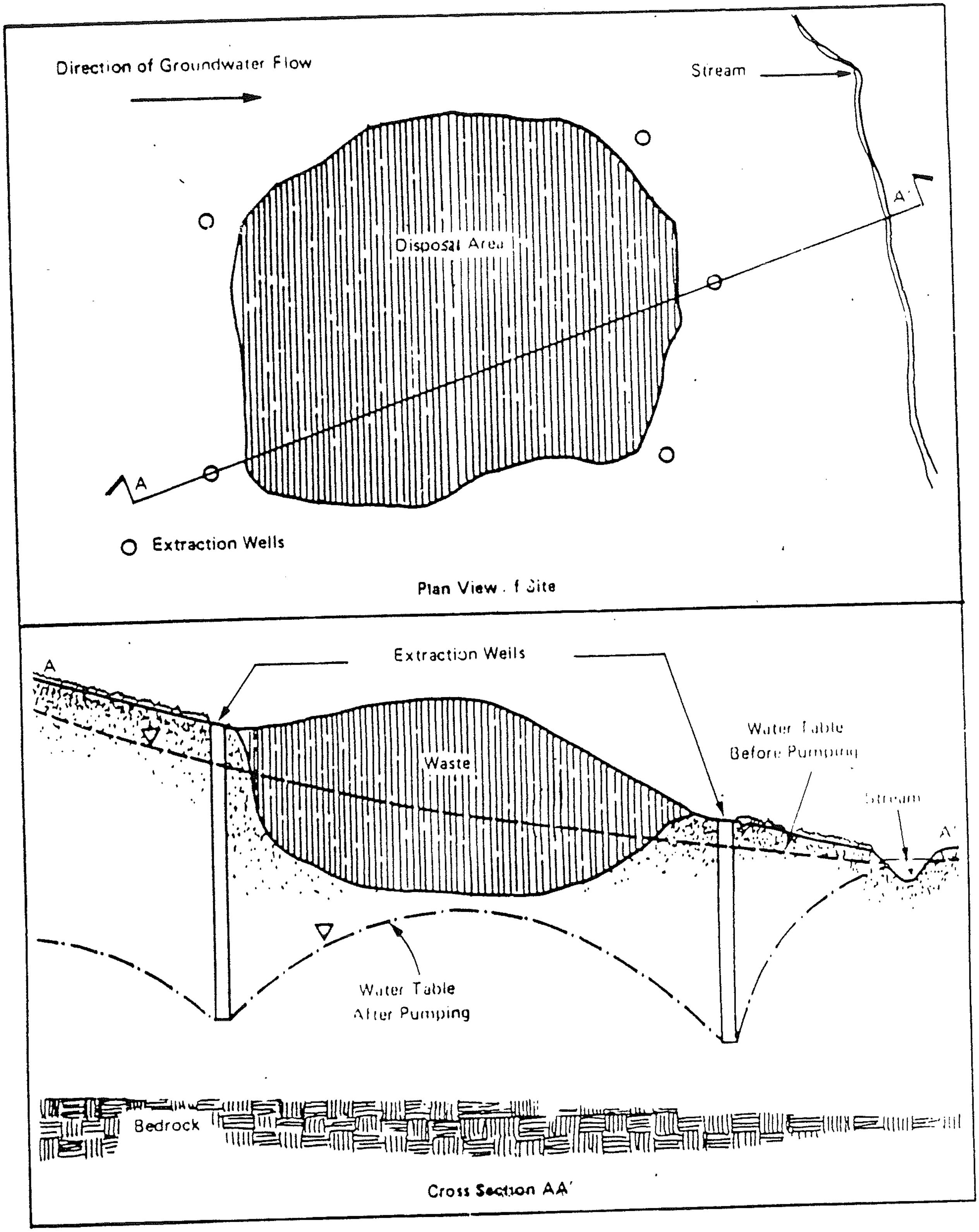


Plane View

[(Davis and DeWisc, 1966) As Cited by Edward Repa and Charles Kufs (37)]

(Figure 5)

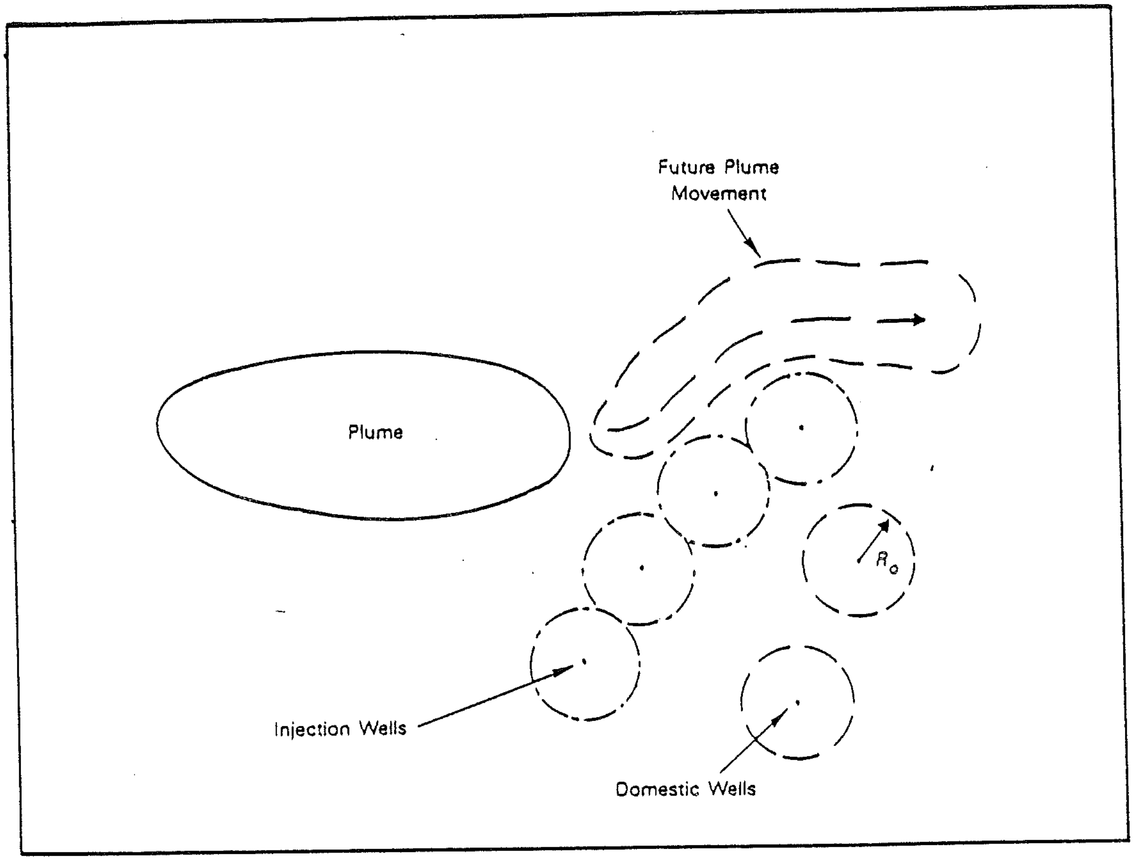
WATER TABLE ADJUSTMENT BY EXTRACTION WELLS



["Handbook for Evaluating Remedial Action Technology Plans" 1983 by John Ehrenfeld and Jeffrey Bass (26)]

(Figure 6)

PLUME DIVERSION USING INJECTION WELLS



["Leachate Plume Management" 1985 by Edward Repa and Charles Kufs (37)]

combination of extraction and injection wells can also be used to flush contaminants from the subsurface to accelerate contaminant removal. There are a variety of patterns of the extraction and injection wells technique that can be used depending upon the site specific characteristics of the area (6, 16, 37, 96).

The effect of hydraulic barriers, recharge and discharge zones, pumping rate, pumping time and cycle, full or partially penetrating wells, original hydraulic gradient, confined or unconfined aquifer, and other aquifer characteristics will determine the size and shape of the cone of depression and the time necessary for the cone to reach equilibrium (see Figure 7). There are manmade hydraulic barriers and natural hydraulic barriers. Manmade barriers include activities done which modify water table gradients, raising or lowering the water table, creating or eliminating recharge and discharge areas, etc. Natural hydraulic barriers inclulde unusually permeable or impermeable areas, intrusions of low permeability matrix, ground water divides, etc. An aquifer's transmissivity (indicative of the capacity of the aquifer to transmit water) and coefficient of storage (indicative of the amount of water which can be removed by pumping) are also very important in determining the cone of depression and constitute the most significant considerations in design of the well system.

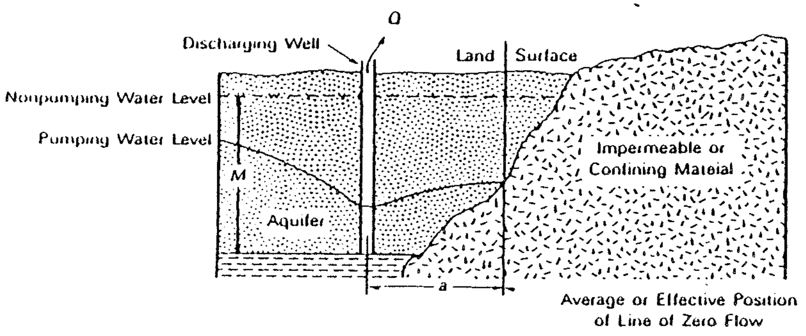
A cone of depression forms more rapidly in a confined aquifer than an unconfined aquifer. Furthermore, the amount of water withdrawn to form a cone of depression is significantly less than would be necessary in an unconfined aquifer. As a result, overlapping cones of depression are easier to maintain in a confined aquifer. In an unconfined aquifer, transmissivity lowers as dewatering occurs. This leads to lower pumping requirements to maintain the cone of depression.

A cone of depression has the greatest impact on the water table, or drawdown, at the well. The drawdown becomes less at greater distances from the well, and eventually is nonexistent (see Figure 8). Some of the basic well equations that describe the interaction of hydraulic characteristics of an aquifer and its response to pumping can be found in citation #37 (well theory). Once the cone of depression has reached equilibrium (cone of depression is stabilized), the horizontal distance from the well affected by drawdown is known as the radius of influence. It is used to determine optimum pumping rates, well

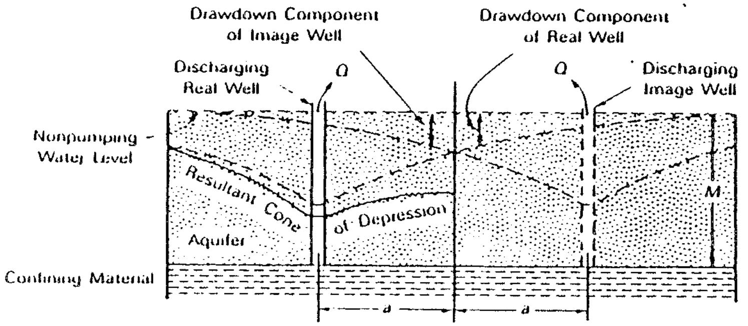
(Figure 7)

METHOD OF IMAGES FOR DETERMINING RESULTANT CONE OF DEPRESSION

Hydraulic Barrier



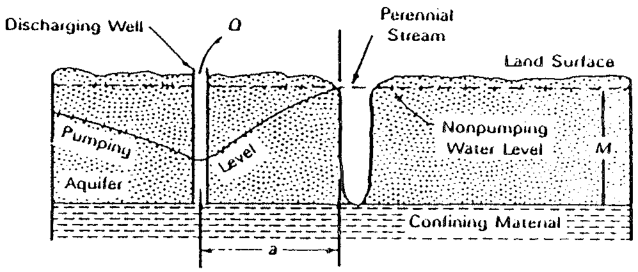
REAL SYSTEM



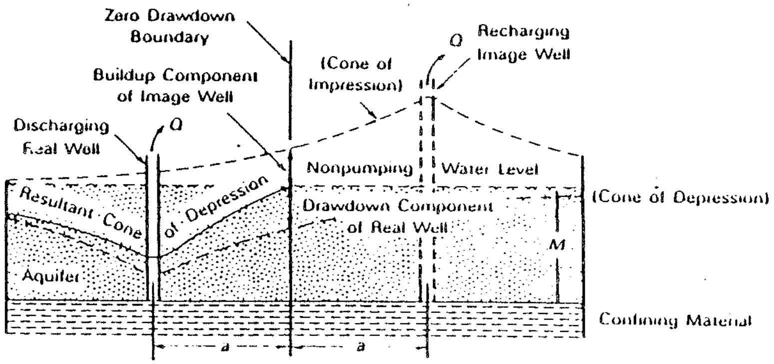
NOTE Aquifer thickness *M* should be very large compared to resultant drawdown near real well

HYDRAULIC COUNTERPART OF REAL SYSTEM

Recharge Barrier



REAL SYSTEM



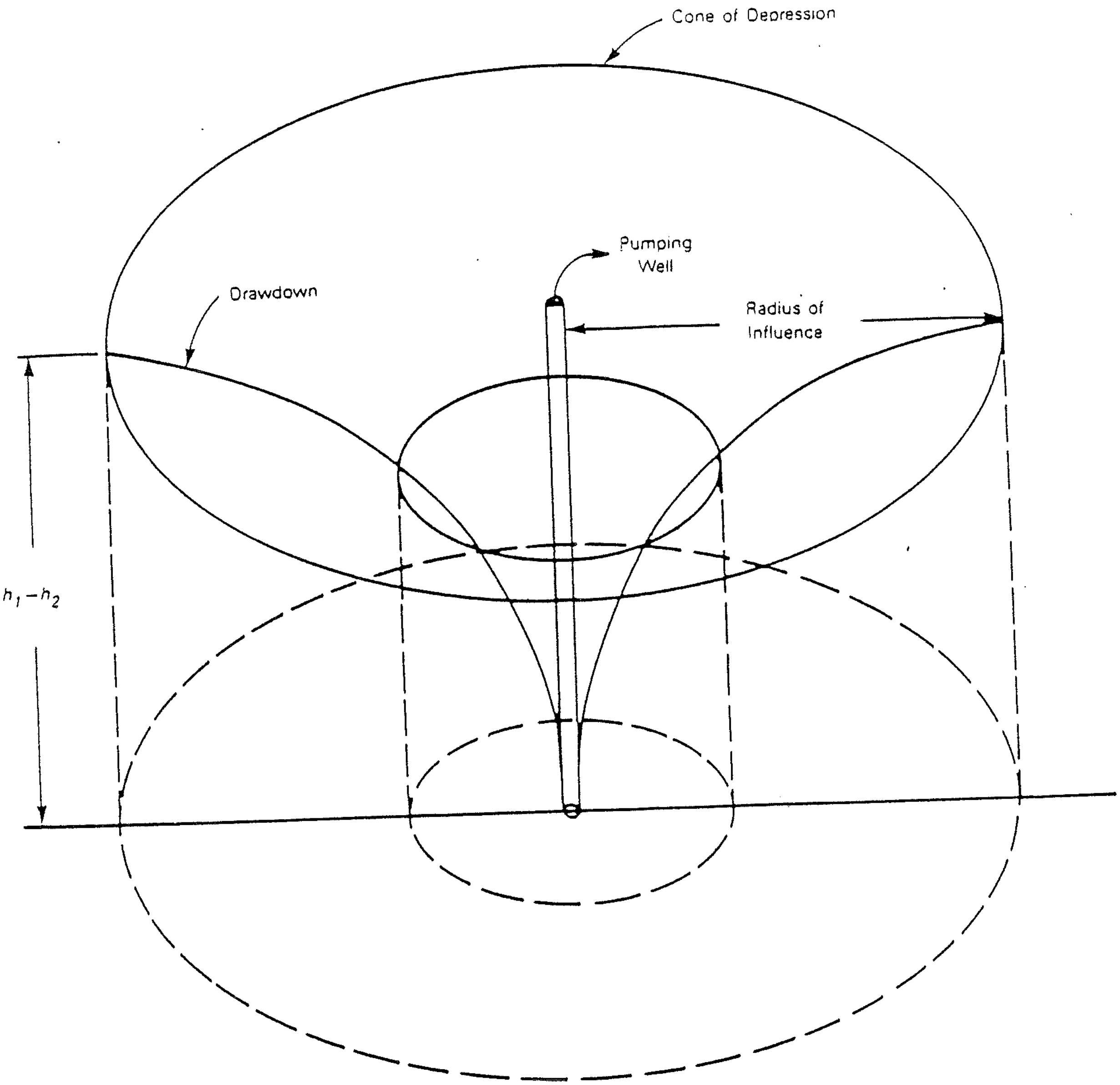
NOTE: Aquifer thickness *M* should be very large compared to resultant drawdown near real well

HYDRAULIC COUNTERPART OF REAL SYSTEM

[(Ferris et al, 1962) As Cited by Edward Repa and Charles Kufs (37)]

(Figure 8)

FORMATION OF CONE OF DEPRESSION FOR A PUMPED WELL



("Leachate Plume Management" 1985 by Edward Repa and Charles Kufs (37)) spacing, pumping cycles, and screen lengths. When extraction wells are being used as a barrier to withdraw the plume, the cones of depression are overlapped to create a hydraulic barrier. Unfortunately, when high transmissivity and moderate to high aquifer flow rates exist, contaminants may pass between overlapping cones of depression. In this instance, velocity plots (112) can be developed so the extraction system can be designed to be a complete barrier and not allow contaminants to pass the barrier. One of the ways velocity plots can be done is by combining Darcy's Law (20, 37) with the standard continuity equation of hydraulics (whatever goes into the system must come out). There are also other means such as tracers, model simulations, etc. (7, 10, 20, 37, 112, 119, 136 and more).

In many situations, particularly when the contaminants are not deep in the aquifer, pumping low flows from several wells (wellpoints) can reduce the overall amount of water that will need to be removed by as much as 60%, while creating a more effective barrier and efficiently removing contaminants. For example, ten wellpoints pumping 10 gpm would normally create a larger radius of influence than would a deep well pumping 100 gpm. Also, having multiple shallow wells, as opposed to fewer deep ones, results in the contaminants having a shorter distance to travel. This possibly reduces the duration and cost of recovery. Finally, having a larger number of smaller cones of depression as opposed to one large one, will expose less soil to the floating contaminants as they are drawn down to the well and extracted. However, if the contaminants are deep in the aquifer, and removal is desired, there is no choice but deep extraction type wells. Pumping high flows from a few deep wells or lower flows from numerous deep wells are both feasible. This choice would depend upon such factors as how well the contaminant plume had been delineated, viscosity and density of the contaminants, depth of aquifer, size of plume, contaminant phase, etc.

In all but extremely simple sites, the details of an extraction system cannot effectively be determined until there are wells installed and tested (pumping tests). These tests need to consider the geology (lithology, structure, and stratigraphy), plume of contamination (areal extent and depth, location in the aquifer and types of contaminants) and aquifer characteristics (confined, unconfined or perched; boundaries; thickness, depths, and formational designations, discharge and recharge zones; hydraulic conductivities, storativities and transmissivities; locations of existing wells; ground water and surface water relationships; and pump test data--drawdowns, pumping rates, cycles, times, etc.) There are numerous types of tests that can be conducted, the scope of this short summary is insufficient to discuss all of the parameters and site specific factors that would determine the optimum type of pumping test. Finally, it is wise to keep the planned extraction system flexible so it can be adjusted to accommodate changing conditions at the site (concentrations, waste levels, flow rates, etc.). The following citations discuss case studies where extraction and/or injection technologies were incorporated (3, 22, 23, 25, 46, 47, 48, 50, 58, 61, 62, 64, 78, 80, 103, 108, 110, 141, 144, 145, 147).

Subsurface Drains

Subsurface drains are permeable barriers that are used to passively collect underground liquid discharges by gravity flow. When combined with a simple pumping system the water can be pumped from the subsurface drain for treatment, creating a cone of depression along the drainage trench. When considering subsurface drains the depth of installation must be considered. The drain(s) will need to be installed at a depth determined by site specific factors (depth to contaminants, geology, hydrology, etc.). At great depths this technology can be prohibitively costly. Much of the costs incurred depends on the type of soil/bedrock (indicative of the amount of effort needed to excavate and ability of the soil to maintain the sidewalls of the trench during construction) that is being excavated and the method of excavation. Normally backhoes are used, but other methods such as clamshell buckets on a dragline can achieve greater depths. The main elements of a subsurface drain include drain pipes or gravel bed (for diverting flow to a wet well or storage tank), manholes (used to collect leachate and pump to surface), backfill (prevents ponding and brings the drain to grade), envelope (used to direct collected leachate from aquifer to the drain pipe), filter (to prevent clogging), and pumping stations.

In some situations where hydraulic conductivity is low or variable, the cost of using pumping/recharge systems can be prohibitive because the wells will need to be spaced very close together. In this instance, subsurface drains are generally effective. Conversely, areas with high hydraulic conductivity and high flow rates are often inappropriate situations for subsurface drains, because the system would need to have such a large capacity. A final problem that can arise with subsurface drains occurs when the contaminants are reactive or viscous, because this may result in clogging and corrosion of the drainage system.

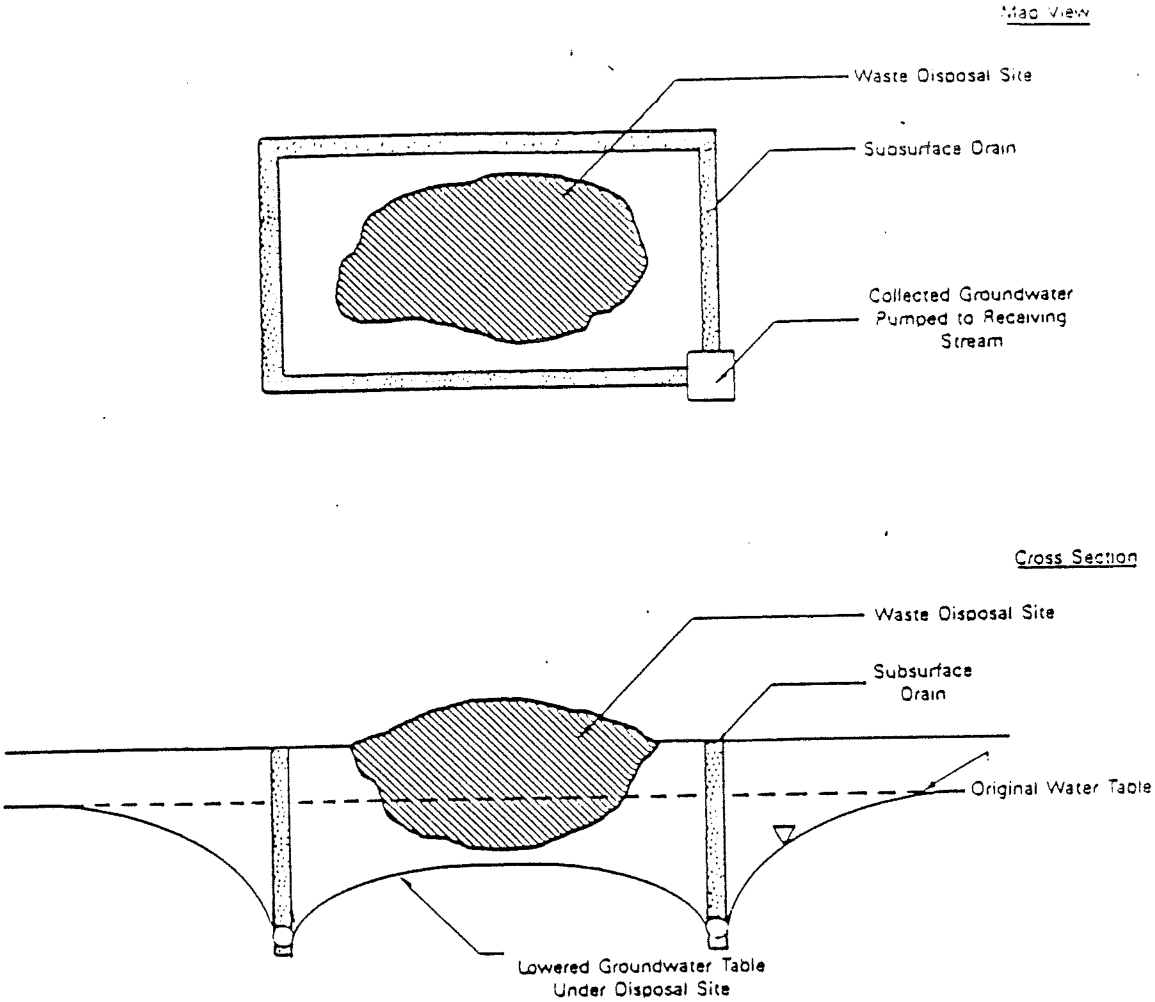
The two basic types of subsurface drains are interceptor drains and relief drains. Interceptor drains can be used to collect ground water from an upgradient source (see Figure 1). They are often used to stop contaminant migration from reaching supply wells or surface waters that are hydraulically downgradient from the contaminant source. These types of drains are installed perpendicular to the ground water flow direction and at the tow (leading edge) of the plume. On the other hand, relief drains are normally used to lower the water table around a site, to prevent the contaminants from contacting the ground water, and to prevent the contaminants from reaching deeper underlying aquifers. Relief drains perform best in areas with a relatively flat hydraulic gradient (see Figure 9). A contaminated site can be completely surrounded by relief drains to prevent contaminants from migrating off-site. Relief drains are similar to barrier wells in that they are installed on each side of the waste site to create an area of drawdown so contaminants cannot flow between the drain lines. The following citations present case studies where subsurface drains were employed (19, 43, 141, 145).

Low Permeability Barriers

Low permeability barriers are another containment technology that is fairly well documented. They are a material placed in the subsurface that is less permeable than the surrounding subsurface. There are three main types of low permeability barriers used in plume containment and management. These types are slurry walls, grout curtains, and diaphragm walls. These barriers can be used to completely surround and contain a plume or waste site, to divert ground water flow, or (when combined with a pumping unit) to lower the ground water table so it does not contact the waste. One of the major concerns with low permeability barriers is that the plume of contaminants may flow underneath the barrier if the barrier is not connected to a natural formation also with low permeability. Some of the

(Figure 9)

THE USE OF SUBSURFACE DRAINAGE TO LOWER GROUNDWATER LEVELS



["Leachate Plume Management" 1985 by Edward Repa and Charles Kufs (37)]

other potential problems include increasing the head upgradient which may effect vertical flow, and the bathtub effect inside a closed area. In this case (bathtub effect) there would need to be internal pumping.

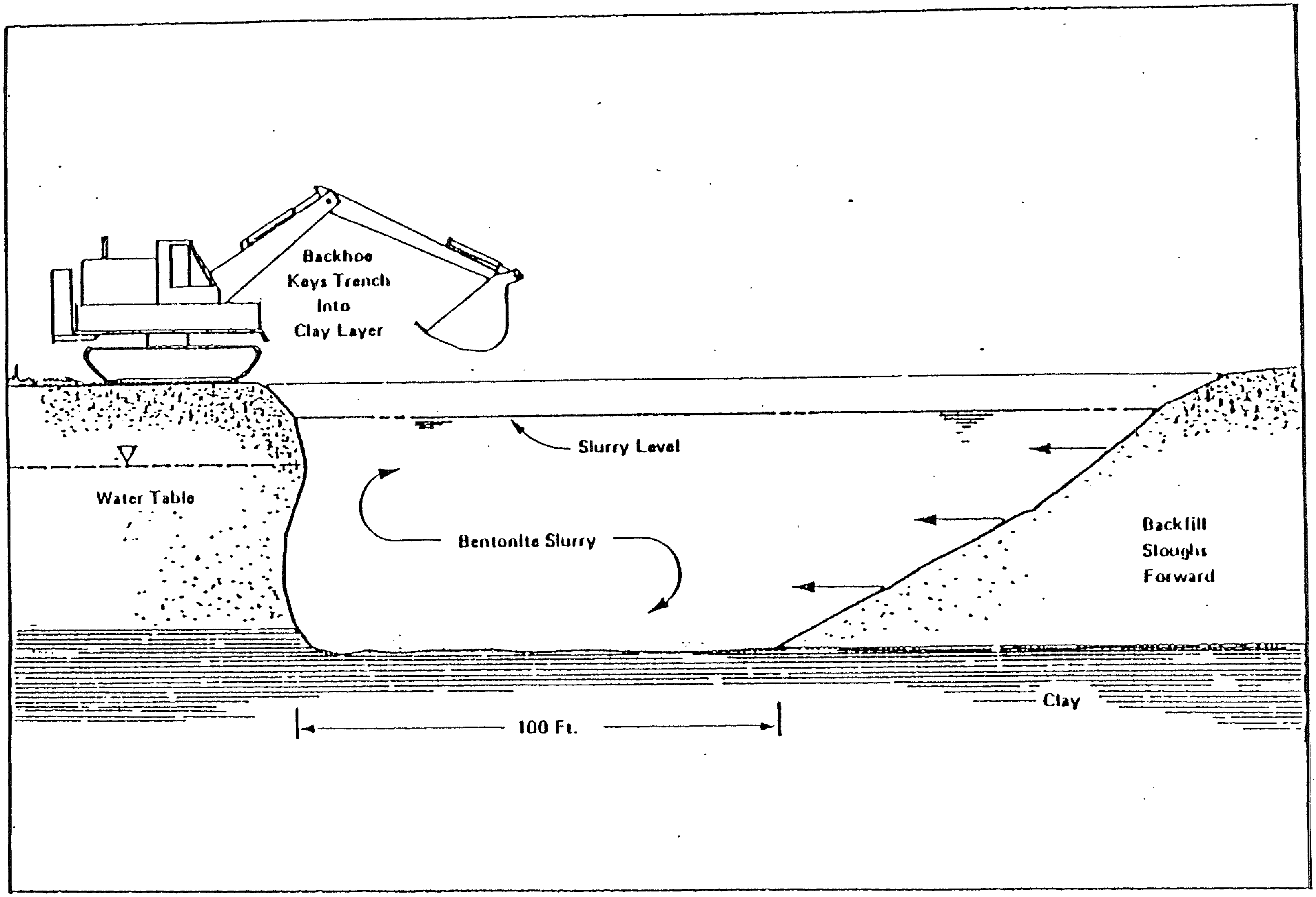
Some of the main types of slurry walls include soil bentonite, cement bentonite, plastic cement, and compacted clay. Slurry walls are excavated using a high density slurry, often bentonite and water, to support the sides. The trench is then backfilled with material having a lower permeability than the surrounding subsurface material (see Figure 10). This lower permeability barrier then reduces the flow through or redirects ground water flow around the barrier.

Grout curtains are formed when grout (a special fluid that seals and strengthens rock or soil bodies) is pressure injected into the subsurface. The grout then gels in the subsurface and fills gaps and voids in the ground to make a stronger, less permeable grouted mass (see Figure 11). Grouts are generally not practical when the subsurface environment is not consolidated (i.e., sands and gravels). In this case, it becomes difficult to get a uniformly low permeable barrier. Grouts perform best when they are used in porous or fractured rock to seal voids and cracks. There are numerous types of grouts, each performing better depending on the specific environment (5, 37).

The third type of low permeability barrier that will be discussed is the one that is probably least employed. Diaphragm walls are installed using a backhoe or clamshell bucket. The trench that is dug is supported by slurry. The diaphragm wall itself is a precast or cast in place reinforced concrete panel or tremied concrete around a reinforcement cage. Diaphragm walls are used when structural strength is needed along with low permeability. However, they are not only the strongest but also the most costly. Diaphragm walls as well as grout curtains are limited as to what depth they can be installed. It is possible to construct trenches using a clamshell bucket and drag line, to great depths. However, at such extreme depths these types of barriers are normally not cost effective. The depth at which these barriers become prohibitively costly depends upon site specific conditions including depth of aquifer, type of contaminants, type of subsurface environment (soil, bedrock), etc. Two other technologies that can be employed are vibrating beams and sheet

(Figure 10)

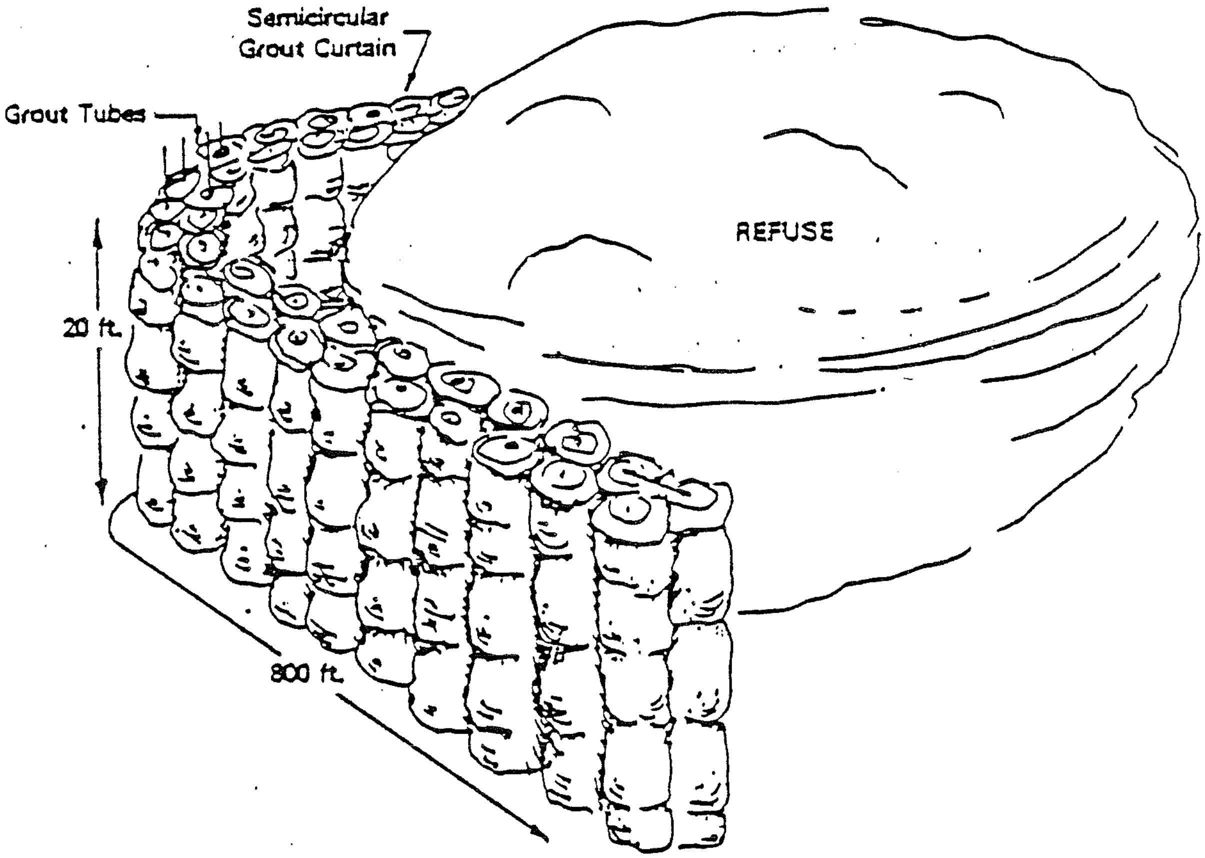
CONSTRUCTION OF A BENTONITE SLURRY WALL



[(Sommerer and Kitchens, 1980) As cited by Arthur D. Little, Inc. (11)]

(Figure 11)

SEMICIRCULAR GROUT CURTAIN AROUND UPGRADIENT END OF LANDFILL



["Evaluation of Available Cleanup Technologies for Uncontrolled Waste Sites" 1984 by Arthur D. Little, Inc. (11)]

piling. Vibrating beams are vibrated into the subsurface. As they are withdrawn the voids are filled with low permeability materials. Sheet pilings are driven into the subsurface and used as low permeability barriers.

When using low permeability barriers it is important to have a thorough understanding of the interactions of the waste and/or leachate on the low permeability barrier material being used. Some wastes and/or leachates have been shown to deteriorate the structure and permeability of some barriers. This barrier/waste interaction is dependent upon the type of material used for the barrier, type of subsurface environment, rate of waste migration, interactions of various contaminants while in the subsurface, etc. The scope of this summary is not to try to define those various interactions. These contaminant/barrier interactions are documented in the literature in the bibliography (5, 18, 53, 127, 128, 151). Case studies are also documented where low permeability barriers were used (18, 19, 22, 46, 51, 93, 110, 133).

Innovative Technologies

The final of the four main technologies is that of the innovative technologies. Since these technologies are relatively new, conclusive documentation of their effectiveness is not readily available. As a result, the main scope of this bibliography concentrates on the other three plume technologies, and this summary is fairly brief. The following innovative technologies are currently being developed: biological in-situ treatment, in-situ chemical treatment, block displacement, and others. In general, these technologies involve treatment or isolation of the waste in place.

In-situ bioreclamation uses microorganisms (native or introduced) to accelerate biodegredation of contaminants. The microorganism growth is often enhanced by the introduction of nutrients and oxygen to the plume. One fairly well documented use of this approach combines in-situ treatment with withdrawal wells. The wells are used to stop the migration of the plume. The water withdrawn can then be treated with nutrients and/or bacteria inoculated into the water and then be recirculated through the plume to enhance in-situ biodegredation in the aquifer. In some cases, air, oxygen, or hydrogen peroxide can be injected directly into the plume to enhance the microbial activity and thus contaminant degradation (see Figure 12). The plume must be well defined for this method to function. Also, the contaminants must be susceptible to biodegradation.

In-situ chemical treatment involves the injection of chemicals into the plume that detoxify, neutralize, or precipitate the contaminants (see Figure 13). The major types of in-situ chemical treatment includes soil flushing, precipitation/polymerization, oxidation/reduction, neutralization/hydrolysis, and permeable treatment beds.

Soil flushing involves the introduction of solvent to the contaminant source, allowing it to enter the ground water through the same pathway followed by the contaminants to remove residual contamination from the soil, thus preventing further leaching. Solvents include water, water and a surfactant, complexing agents, and dilute acids and bases. Soil flushing appears to be the most promising when used for the removal of organics and metals. One of the drawbacks is that it may be necessary to collect and treat materials that have been flushed out of the soil. Furthermore, understanding of local hydrogeology and the contaminant properties should be obtained.

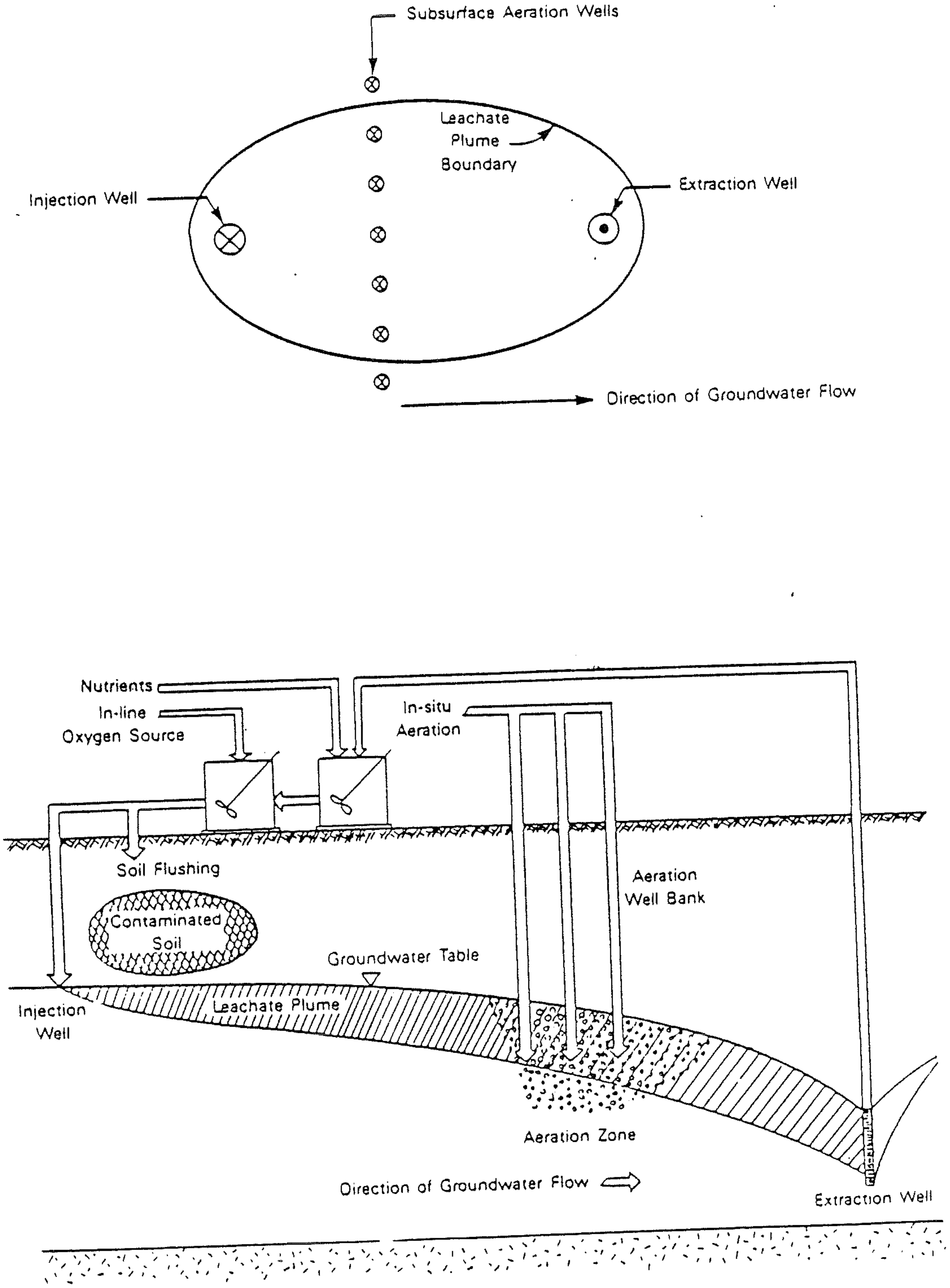
Precipitation/polymerization removes the contaminant from the ground water by making them insoluble. By introducing a reactive substance (or catalyst) into the ground water plume, an insoluble precipitate that does not flow with the ground water is created, thus stopping contaminant migration (37).

Oxidation/reduction is used to decompose an organic contaminant to a less toxic, more biodegradable, more soluble form. Hydrogen peroxide, ozone, and hypochlorite are three examples of oxidizing agents. These are easily degraded in the subsurface environment and normally do not form toxic compounds or residuals (37).

Neutralization/hydrolysis uses acids or bases to adjust the pH. This treatment can be used as a means to degrade organic chemicals, prevent toxic gas formation, promote

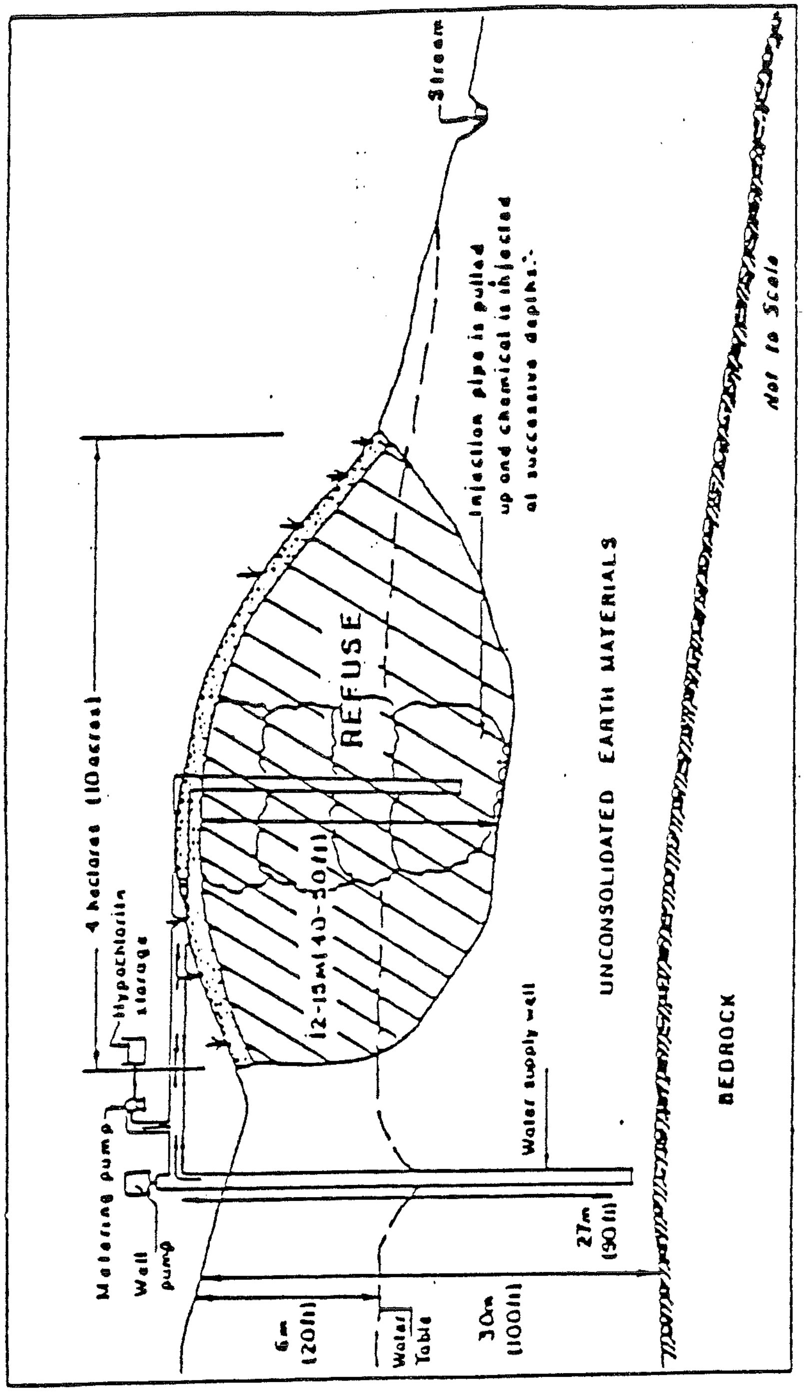
(Figure 12)

SIMPLIFIED VIEW OF GROUNDWATER BIORECLAMATION



["Leachate Plume Management" 1985 by Edward Repa and Charles Kufs (37)]

(Figure 13)



CROSS SECTION OF LANDFILL TREATED BY CHEMICAL INJECTION

["Evaluation of Available Cleanup Technologies for Uncontrolled Waste Sites" 1984 by Arthur D. Little, Inc. (11)]

bioreclamation and chemical treatments, and as a post treatment method to restore the original pH (37).

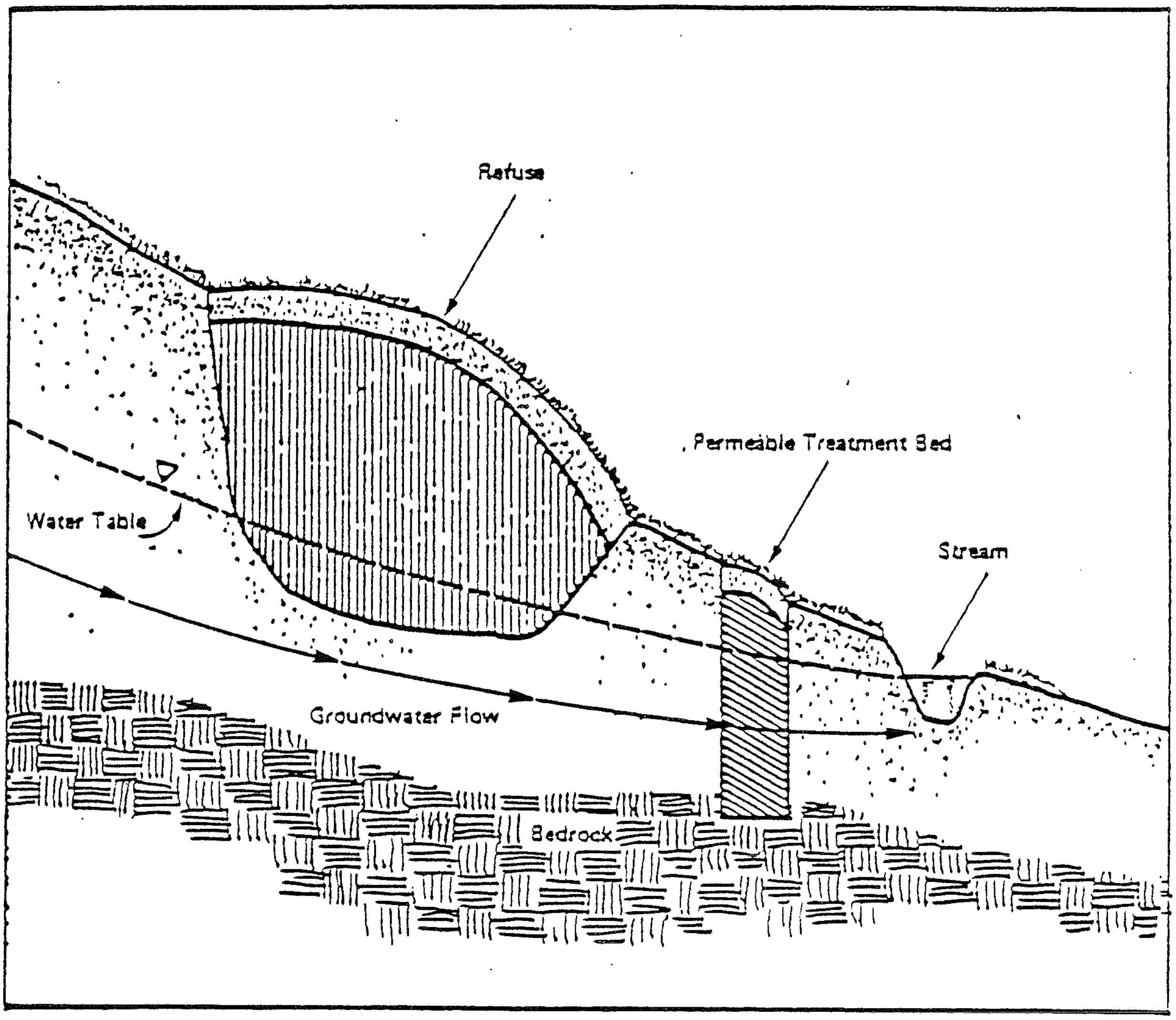
Permeable treatment beds are trenches that are backfilled with materials such as activated carbon, limestone, crushed shells, etc. that treat the contaminated plume as it flows through the barrier (see Figure 14). This is a relatively untested technology that is thought to be most useful for reducing the quantity of contaminants in a leachate plume, not for complete removal, and is limited by depth.

All in situ treatments, except perhaps permeable beds, are only useful on relatively homogenous waste types. Sites contaminated with a wide variety of wastes will probably not be able to take advantage of these developing technologies unless they are used as only part of the treatment scheme.

The final innovative technology that will be discussed is that of block displacement. Basically, the contaminated soil is displaced by pumping slurry into interconnected underground injection holes. As this slurry is pumped into the ground vertical displacement occurs. The slurry forms a low permeability barrier that encapsulates an entire block of earth (see Figure 15). Block displacement would be best employed when there is no low permeability barrier below a waste site (at depths where other contaminant technologies, such as slurry walls, are not practical). In theory, block displacement completely encapsulates a waste site. This is an attractive remedy for containment. However, it is difficult to ensure that once a block is displaced that it is totally encapsulated, or if the impermeable barrier is thick enough throughout (11, 26, 37, 106, 129).

Contaminant Characteristics

Besides aquifer characteristics, another important consideration to keep in mind when selecting a containment and/or management technology is that of the contaminant characteristics. These main characteristics include volume, density, viscosity, solubility, temperature, and attenuation. The volume of contaminated ground water is important



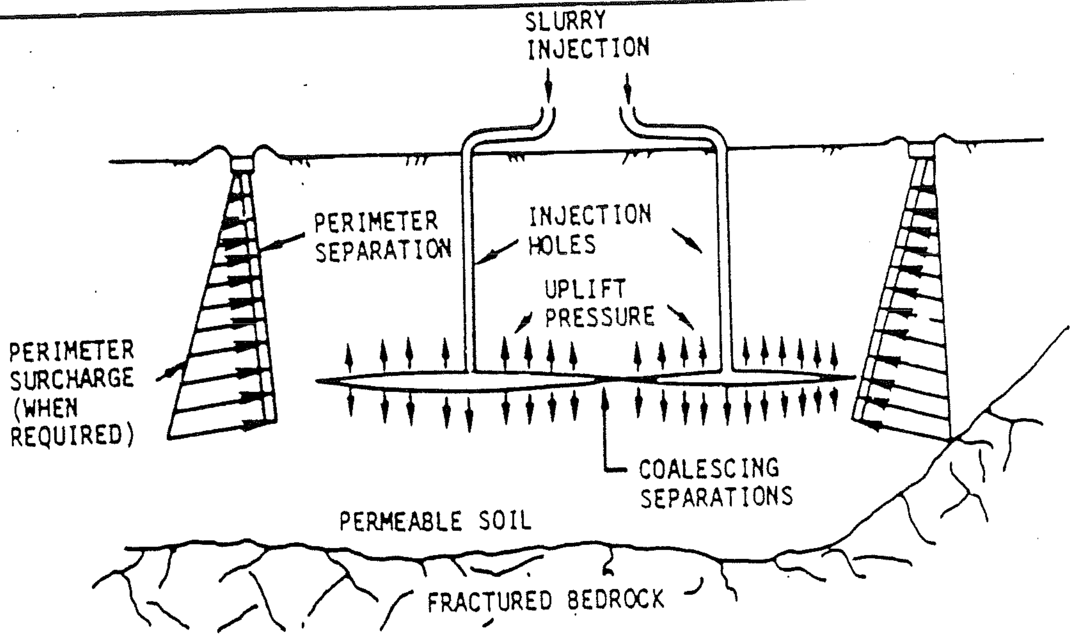
(Figure 14)

INSTALLATION OF A PERMEABLE TREATMENT BED

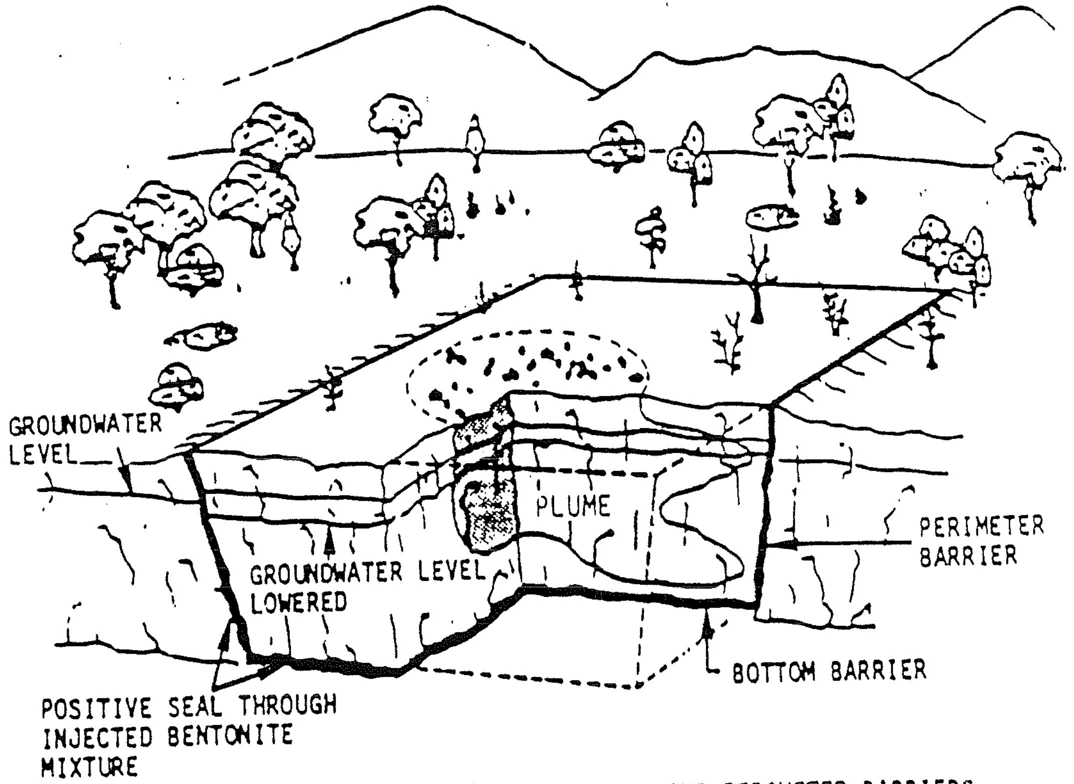
["Evaluation of Available Cleanup Technologies for Uncontrolled Waste Sites" 1984 by Arthur D. Little, Inc. (11)]

(Figure 15)

BLOCK DISPLACEMENT METHOD



a) CREATING THE BOTTOM SEPARATION



b) CONFIGURATION OF FINAL BOTTOM AND PERIMETER BARRIERS

["Handbook for Evaluating Remedial Action Technology Plans" 1983 by John Ehrenfeld and Jeffrey Bass (26)]

because it determines the amount of water that will need to be dealt with. The more contaminated ground water there is the more that will have to be contained and/or removed. Precipitation, temperature, percolation (infiltration) rates of water, and subsurface characteristics effect the amount (volume) of contaminated ground water that can be produced.

The density of the contaminants plays a very important role in the type of plume that will be produced. Low density contaminants, such as petroleum products are less dense than water. These contaminants will generally accumulate on top of the aquifer and can form a lens of contamination that can be several feet thick. High density contaminants, such as brines, are heavier than water and will sink to the base of the aquifer. In some instances, leachates can contain both high and low density contaminants. In this case a complex two or three plume system can be present. A complete analysis of leachate from the source of contamination can be helpful in determining how the wastes will migrate once in the subsurface area (see Figure 16).

The size and shape of the contaminant plume is further influenced by the solubility of the contaminants. When the contaminants entering the leachate are miscible, generally a larger more dispersed plume is formed. When the contaminants are immiscible, a smaller more concentrated plume is likely (see Figure 16).

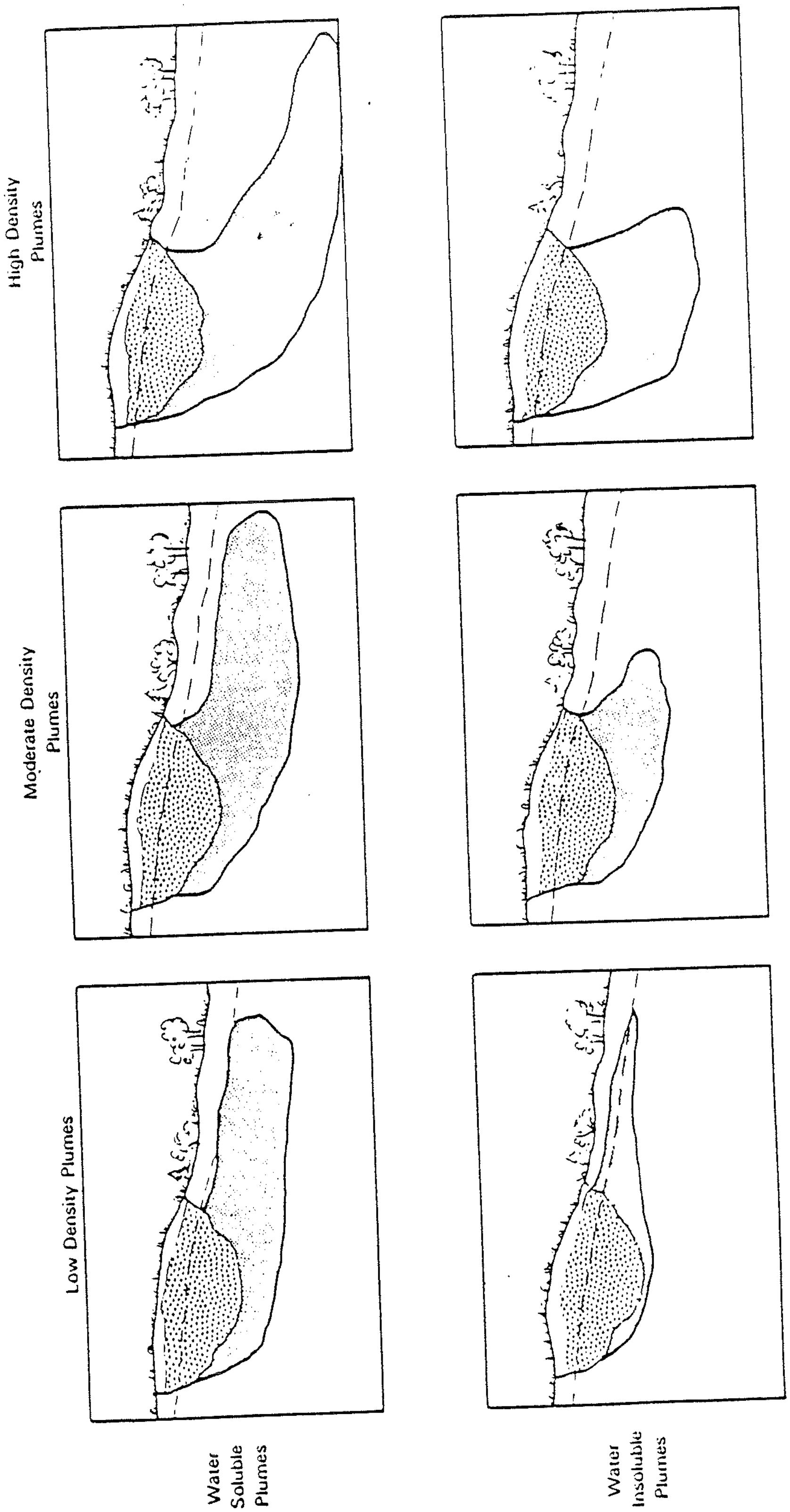
If a contaminant has a high viscosity it should flow slower than one with a lower viscosity. It would create a smaller (less dispersed) plume of contamination.

Another important contaminant characteristic is temperature. Higher temperature (possibly from aerobic degradation in the aquifer) leachates become less dense than the same leachate at a cooler temperature. This could have a bearing on where in the aquifer the contaminants can be found.

A final leachate characteristic that can influence the size, shape, and concentration of a plume is attenuation. Attenuation occurs when contaminants are biochemically degraded, precipitated or sorbed into the subsurface matrix. Attenuation of contaminants in the

(Figure 16)

CONFIGURATIONS BASED ON SOLUBILITY AND DENSITY



["Leachate Plume Management" 1985 by Edward Repa and Charles Kufs (37)]

subsurface is an extremely complex process. It is influenced by the type of geologic matrix in the subsurface, physical and chemical characteristics of the leachate and ground water, subsurface flow rates, type of contaminant, etc. These interactions are not within the scope of this paper. The document "Leachate Plume Management" (37) discusses attenuation. All of the above mentioned contaminant characteristics effect the size, shape and location of the plume, and can be important when considering the various containment and management technologies available.

Modeling Plume Characteristics and Behavior

There are numerous models available for determination of the optimum design of plume containment and management systems. These simulations have been shown to be good indicators of performance of full scale containment and management systems, if the necessary information used is complete and accurate (7, 10, 16, 29, 35, 48, 52, 109, 112, 119, 135, 136).

The main types of models are mathematical and physical. Both types of models attempt to simulate actual aquifer behavior. An example of a physical model is a laboratory sandpack. These types of models simulate full-scale systems by using a smaller scale, controlled environment similar to that of the natural environment of concern. Mathematical models can be either analytical or numerical. Analytical models use assumptions and simplifications, but do provide exact solutions. Some examples of these assumptions and simplifications include homogeneous aquifers, constant hydraulic properties, and uniform infiltration rates. Analytical models provide a quick and inexpensive evaluation, and are good in cases where simplified assumptions are valid and when a lack of data prevents the use of numerical models. In general, numerical models can address more complicated problems because they are not as limited by simplifications and assumptions. However, they require much more data and the solutions they provide are numerical approximations, and are not exact. Mathematical models are limited within the context of the assumptions, simplifications, and data upon which they are based, but can provide an important input in plume containment and management efforts. An overview of these models is available in

"Ground Water Handbook" EPA/625/6-87/016 (20). Because there are numerous models available, it is important to be aware of the various models available and how they perform.

For a model to be successful one must have a thorough understanding of the aquifer characteristics, recognize the limitations of the models, and realize how critical it is that correct information be input into the model. Some of the input information needed includes contaminant concentration and density; aquifer porosity, transmissivity, storage coefficient, thickness, specific yield, hydraulic gradient, cross sectional area, and hydraulic head; height of water in well; contaminant degredation rate, dispersion, molecular diffusion and time in subsurface; and other variables.

Some of the information obtained from these models include the prediction of optimum pumping and injection rates; drawdown obtained; optimizing overlapping cones of depression; contaminant transport rates; ground water flows--with and without the various technologies available; time required to remediate problem; optimization of number and depth of wells, drains and barriers; and other outputs.

The Hazardous Waste Investigation and Cleanup Program (HWICP) has a number of models available concerning various aspects of ground water. These include MOC, MUDFLOW, SUTRA (USGS models to analyze ground water contamination problems), PUMP TEST (geologic cross-section and wellfield simulation programs), RESSQ, AT123D, AGU-10 (for analysis of ground water problems), EXAMS, MINTEQ (EPA's programs on ground water and surface water problems), and RANDOMWALK. A final model that could prove helpful is the HELP model (analysis of water movement into, through and out of landfills).

There is a separate bibliography at the end of the paper that discusses in-situ technologies. These were pieces of literature that were collected while searching for other plume containment and management technologies. This is not a complete bibliography on in-situ technologies but does provide a good overview of the types of literature available on in-situ treatment.

Summary

In summary, the general design considerations for most containment systems will need to include a thorough understanding of the topography (somewhat indicative of the underlying structure, elevation, drainage patters, landslide problems, traffic patterns, flood potential, etc.), geology (gives the structure, stratigraphic matrix, and regional conditions), hydrology (indicative of porosity, permeability, gradient, can gain information with pump tests - helps determine screen size and setting, well spacing, depth, pumping rates, etc.), waste characteristics, (compatibility between materials used and wastes, the leachate viscosity, density, solubility, volume, temperature, and degree of dispersion - all considered for designing screen size, gravel pack medium, well depth, and pump type and size), and materials used in remediation (must be compatible with the contaminants, anticipated life of structure, replacement costs, maintenance costs, and climatic conditions).

The titles in the bibliography are generally indicative of the types of subjects discussed in each particular piece of literature. As previously mentioned, this brief summary should be used only to provide an overview of most of the subjects discussed in the literature contained in the bibliography.

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