Guidance for Design, Installation and Operation of Groundwater Extraction and Product Recovery Systems

PUB-RR-183 November 2003 (Reviewed August 2014)

Purpose:
This is a guide to using groundwater extraction and product recovery as a remediation technology. Groundwater extraction systems are systems that pump contaminated groundwater from an aquifer on a long-term basis. Groundwater extraction requires treatment and proper disposal of the pumped groundwater. Groundwater that is treated on-site can be discharged to surface water or groundwater under a Wisconsin Pollution Discharge Elimination System (WPDES) permit. Treated groundwater (on-site or off-site) may also be discharged to a publicly owned treatment works (POTW) provided that prior approval is obtained from the POTW.

Most of this guidance is specific to remediation of unconfined aquifers, however, much of the guidance is also appropriate for confined aquifers. An aquifer is defined in this document as any soil or rock unit that contains water under saturated conditions. The term aquifer, as used in this document, can refer to a unit that is overlain and/or underlain by a geologic unit that has relatively higher permeability, and/or does not produce economically significant volumes of water.

Product recovery refers to physically removing free product from the aquifer by pumping. In almost all cases, product recovery refers to extracting floating product from the aquifer. Recovery of sinking product (dense non aqueous phase liquid or DNAPL) by pumping is also considered product recovery.

Because each site has unique characteristics, it may be necessary for system designers to deviate from the guidance. The DNR acknowledges that systems will deviate from this guidance when site-specific conditions warrant. When deviations occur, designers should document these differences in their work plan to facilitate DNR review. For additional information on the DNR's permitting and regulatory requirements, please refer to Subsection 1.3 in this document.

Author/Contact:
This document was originally prepared by George Mickelson who no longer works for DNR. It was reviewed for accuracy by Gary A. Edelstein (608-267-7563) in August 2014.

Errata:
This document includes errata and additional information prepared in August 1995. The rule cites and references to other DNR guidance in the document were also reviewed and found to be current, with the exception of publications SW-157, "Guidance for Conducting Environmental Response Actions" and SW-184, "Guidance for Treatment of Groundwater and Other Aqueous Waste Streams", which are no longer current guidance documents.

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Additional information, changes, clarification and errata to the *Guidance for Design, Installation and Operation of Groundwater Extraction and Product Recovery Systems* includes the following:

- Transmissivity is misspelled throughout the entire document, it should be transmissivity, not transmisivity.

- DNR Rules. This guidance document was completed prior to the effective date of the NR 700 series of rules. There are many additional requirements within NR 724 for submittal contents that are not included in this document. Also, there may be other requirements in other chapters that affect an individual project.

- Section 3.0. Laboratory Permeability Tests. Laboratory permeability tests are not recommended for designing ground water extraction systems. Unless special procedures are used, the test quantifies vertical permeability, not horizontal permeability. Since most of the ground water flow to a ground water extraction system is horizontal, measuring the horizontal permeability is more appropriate. The only times that laboratory permeability tests should be considered are for evaluating vertical permeability for determining site specific soil cleanup standards under NR 720.

- Subsection 3.3. Pumping Tests and Yield Tests. Pumping tests, as that term is used in the guidance are tests conducted at constant pumping rates for determining aquifer transmissivity. Step drawdown tests which are conducted at two or more constant rates are also considered pumping tests. In both cases, drawdown is measured in the extraction well and other monitoring wells at the site. Drawdown measurements are then used to calculate transmissivity.

  Yield tests, are tests where the well is pumped at or near capacity without collecting the data necessary to calculate transmissivity. Yield tests are not suitable substitutes for pumping tests. If transmissivity (or hydraulic conductivity) is not calculated, plume capture calculations cannot be performed. A yield test is not a pumping test and should not be called a pumping test.

- Subsection 4.1. Plume Capture Calculations. A few consultants have not been calculating plume capture zones. Instead they have referred to the area where there was measurable drawdown during a pumping test or a yield test as the plume capture zone. A measured zone of influence during a short term pumping test cannot be used to predict a zone of capture.

- Subsection 4.1 and Example Plume Capture Calculations. The example plume capture calculations may only be used when the underlying soil layer can be assumed to be impermeable (this was listed in the assumptions). If the underlying hydrogeological unit is more permeable than the overlying hydrogeologic unit that contains the contaminants, there may be significant vertical recharge to the extraction well upward from the underlying unit. In this case, the example methods underestimate the extraction rate that is necessary to contain the plume.

Unfortunately when the transmissivity of the underlying unit is significantly larger than the transmissivity of the upper contaminated hydrogeologic unit, there is no simple analytical solution to calculate the capture zone. The use of a three dimensional computer model may be needed to accurately estimate an accurate pumping rate and well configuration in this situation.

- Subsection 4.1. Maximum Well Yield and Attachment 4. Some well systems have been installed that do not produce an adequate extraction rate. In some of these cases, the Cooper and Jacob formula (or other model) was used to predict drawdown at the desired flow rate from the extraction well, but the well still did not deliver that flow rate. Gefell, et al. (1994) provide example calculations based on the work of Kozeny (1953) that incorporated additional assumptions. Those formulas may be a more realistic way to estimate the maximum yield of a ground water extraction well.

  One of the model assumptions is that the well is a fully penetrating well, the thickness of the aquifer is the same as the length of the saturated screened interval. When the well is partially penetrating the aquifer, two solutions should be calculated, one using the screened interval (for parameter "H") and one using the aquifer thickness. It is likely that the actual maximum yield of the well will be between those two maximum yield solutions. When the parameters from the numerical example in Attachment 4 are used in the formulas from Gefell, et al. (1994), the predicted maximum yield from that extraction well will be between 0.52 and 0.94 gpm depending on which value (aquifer thickness or screen interval) is used for the "H" value in the formulas. Both of these estimates are less than the value predicted by the Cooper and Jacob solution that was used for the example drawdown estimate.

- Subsection 4.2.1.2. Well Design and Well Development. Ground water extraction wells used for remediation are more prone to geochemical and biological fouling than extraction wells in clean aquifers. For these reasons, several issues relating to well development have been raised, as follows:

  - When selecting well screens and casings, well development methods that may be used during the life of the project should be considered. Rigorous development may damage plastic screens and casings.

  - Hydrofracturing and pneumatic fracturing SHOULD NOT BE USED for well development. Locations of induced fractures are unpredictable. As a result, the fractures may intersect clean zones of the aquifer, resulting in short circuit routes. This could result in the system not containing the plume if clean water is extracted via a short circuit route instead of contaminated water.

  - The *Release News*, Volume 4, Number 1, Pages 8 and 9 contains information on chemical rehabilitation of wells. That information is repeated below at the end of these errata sheets.

  - In addition to the information in the *Release News*, the use of additives that contain phosphorous are not recommended for well rehabilitation, these materials may promote biological activity, which may promote increased biofouling in wells.

- Subsection 4.3. Pneumatic Pumps. If pneumatic pumps are used, the exhaust vent must be located in a place that will not restrict the compressed air from exhausting. Restricting the compressed air from freely exhausting could cause over pressurization of other components, resulting in explosion.

- Subsection 4.4. Control Panels and Logic Faults. Control panels must be designed so that inadvertent catastrophic events are avoided. In one situation, after a product recovery system was shut down, a control system design fault allowed the product recovery pump to continue pumping. The product storage tank was then overfilled which ruptured the tank. Control panels should undergo sufficient testing to assure that similar occurrences are not repeated.

- Subsection 4.4. Pitless Adapters. Clamp on type pitless adapters on PVC casing or other casing material that is somewhat flexible is not recommended, leakage may occur. Clamp on type adapters may however be used on PVC or other plastic casings for the vacuum air line for vacuum enhanced recovery systems. In this case, a small amount of air leakage into the line is not a concern.

- Section 6. References. Add the following references:

Gefell, M.J., Thomas, G.M., and Rossello, S.J. 1994. Maximum Water-Table Drawdown at a Fully Penetrating Pumping Well. *Ground Water*, Volume 32, Number 3, Pages 411 to 419.

Kozeny, J. 1953. *Hydraulik: Ihre Grundlagen und Praktische.* Anwendung. Springer-Verlag, Vienna.

The following information on well rehabilitation is repeated from the *Release News*, Volume 4, Number 1, Issued February 1994 (Note: NR 112 was renumbered to NR 812 on October 1, 1994.):

What can be done to limit biofouling of well screens, filter packs and aquifers?

In some situations, the well may need to be replaced. If fines have plugged the well, the well must be redeveloped. In many cases, if the well is poorly designed or installed in clay, redevelopment is required frequently. Driscoll (Driscoll, F.G., Editor. *Groundwater and Wells, Second Edition.* 1986. Johnson Division, St. Paul, Minnesota.) has an excellent discussion of well design, well development, chemical precipitation, and biofouling.

What regulations govern well rehabilitation practices in Wisconsin if it is necessary to add chemicals to rehabilitate a fouled well?

For wells and drill holes which do not qualify as part of a community water system under ch. NR 811, Wis. Admin. Code, rehabilitation practices are governed by administrative rules found in the state's Private and Non-community Well Code (ch. NR 812, Wis. Admin. Code).

Within ch. NR 812, s. NR 812.22 (2) contains specific provisions for the reconditioning of wells and drill holes. Reconditioning includes: redevelopment practices (surging, jetting and overpumping); chemical conditioning (acidification or batch chlorination); and physical conditioning (hydrofracturing and blasting).

For chemical conditioning, the DNR Bureau of Water Supply maintains a list of approved drilling and abandonment aids. Listed materials may be used without obtaining prior approval from the Bureau of Water Supply; however, the reconditioning must be performed by a licensed well driller or under the supervision of a Wisconsin-registered professional engineer.

If consultants need to use a product that is not on the Bureau of Water Supply's "Wisconsin List of Approved Drilling and Well Abandonment Aids," they must get written approval before beginning the reconditioning process.

Questions regarding chemical conditioning may be directed to Tom Riewe, DNR Bureau of Water Supply, 608-266-8697.

Are there any other requirements, regulations and/or permits if chemicals are used to rehabilitate a fouled well?

After the well is chemically conditioned, the discharge of conditioning water from the well must comply with requirements by the regulating authority that approved and/or permitted the discharge. If the discharge is to a publicly owned treatment works (POTW), the POTW may have specific requirements. The DNR Pretreatment program should also be contacted.

A discharge to the ground surface, a surface water, or storm sewer must be authorized under a Wisconsin Pollution Discharge Elimination System (WPDES) permit. The following are examples of criteria that may be in the discharge permit:

- Consultants must receive approval from the wastewater program to use any biocides or surfactants. Biocide levels must also meet the discharge permit's limitations that will be based on toxicity in the receiving water.

- Discharged water must not contain any detectable chlorine.

- Suspended solids in the discharged water must be below 40 mg/L.

- Discharged water must be in the pH range of 6 to 9. Because many well reconditioning chemicals are acids, buffering to raise the pH may be necessary.

In some situations, the initial purge of water from the well may need to be containerized and shipped to an industrial wastewater facility or POTW. A treatment facility is usually required if biocides, other than acids or chlorine, are used. The ERR project manager should also be notified prior to well rehabilitation.

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Figures.

Attachments.

Acknowledgments.

In addition to the many DNR employees who reviewed and commented on drafts of this document, the following individuals also assisted the DNR with reviews and comments:

C. W. Fetter, Ph.D., C.P.G. - University of Wisconsin, Oshkosh.
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Although each of the individuals contributed positively, this document may not represent the views of all reviewers.

Thanks are extended to reviewers for the donation of their time and invaluable input.

Acronyms.

BOD$_5$ — Five-day biochemical oxygen demand

Btu — British thermal units.

DNAPL — Dense Non Aqueous Phase Liquid. DNAPL refers to a non-soluble or semi-soluble liquid with a specific gravity greater than one.

DNR — Wisconsin Department of Natural Resources.

DOT — Wisconsin Department of Transportation.

ERP — Environmental Repair Program of the DNR (state response program).

ERR — Emergency and Remedial Response Program of the DNR.

FID — Flame Ionization Detector.

GC — Gas Chromatograph.

GPM — Gallons Per Minute.

ILHR — Wisconsin Administrative Code that is enacted by the Department of Industry, Labor, and Human Relations has an ILHR prefix. ILHR 10 refers to the rules on storage of flammable and combustible liquids.

LUST — Leaking Underground Storage Tank Program of the DNR.

NR — Wisconsin Administrative Code that is enacted by the DNR has an NR prefix.

PID — Photoionization Detector.

POTW — Publicly owned treatment works.

PVC — Polyvinyl chloride. Material commonly used for pipe, well casing, and well screens.

QA/QC — Quality Assurance/Quality Control.

RCRA — Resource Conservation and Recovery Act.

WPDES — Wisconsin Pollution Discharge Elimination System permit.

1.0 Introduction.

This guidance document is intended to aid environmental professionals in designing groundwater extraction and product-recovery systems for remediating contaminated groundwater. It also provides information to Department of Natural Resources (DNR) staff for efficient and consistent oversight and review.

This document should be read with the existing DNR *Guidance for Conducting Environmental Response Actions*, specifically Chapter 7 (Site Investigation) and when available, Chapter 8 (Remedy Selection).

1.1 Purpose.

This is a guide to using groundwater extraction and product recovery as a remediation technology. Groundwater extraction systems are systems that pump contaminated groundwater from an aquifer on a long-term basis. Groundwater extraction requires treatment and proper disposal of the pumped groundwater. Groundwater that is treated on-site can be discharged to surface water or groundwater under a Wisconsin Pollution Discharge Elimination System (WPDES) permit. Treated groundwater (on-site or off-site) may also be discharged to a publicly owned treatment works (POTW) provided that prior approval is obtained from the POTW (See *Guidance for Treatment Systems for Groundwater and Other Aqueous Waste Streams*).

Most of this guidance is specific to remediation of unconfined aquifers, however, much of the guidance is also appropriate for confined aquifers. The depth of the screened interval and the aquifer-testing methods may differ from the guidance for capturing a plume in a confined aquifer or an aquifer with a submerged plume. If enough piezometers are installed in a confined aquifer to prepare a potentiometric surface map, that map should be prepared in situations where this guidance discusses water-table maps.

An aquifer is defined in this document as any soil or rock unit that contains water under saturated conditions. The classic definition of an aquifer refers to soil or rock units that will produce economically significant volumes of groundwater, and differs from the definition used in this guidance. The term aquifer, as used in this document, can refer to a unit that is overlain and/or underlain by a geologic unit that has relatively higher permeability, and/or does not produce economically significant volumes of water.

Product recovery refers to physically removing free product from the aquifer by pumping. In almost all cases, product recovery refers to extracting floating product from the aquifer. Recovery of sinking product (dense non aqueous phase liquid or DNAPL) by pumping is also considered product recovery.

Because each site has unique characteristics, it may be necessary for system designers to deviate from the guidance. The DNR acknowledges that systems will deviate from this guidance when site-specific conditions warrant. When deviations occur, designers should document these differences in their work plan to facilitate DNR review. For additional information on the DNR's permitting and regulatory requirements, please refer to Subsection 1.3 in this document.

1.2 Scope of Groundwater Extraction and Product Recovery Systems.

Primary goals for groundwater extraction systems are:

- To Contain Contamination to a Specific Zone. Dissolved contaminants are prevented from migrating beyond the capture zone by pumping an aquifer at a sufficient rate from (a) specific location(s).

- To Extract Dissolved-Phase Contamination. Some of the dissolved contamination is physically removed from the aquifer.

- To Create a Cone of Depression for Product Recovery. In some cases, groundwater extraction is used to create a cone of depression to draw non-aqueous phase liquids toward the recovery well.

- To Lower the Water Table for Soil Venting. In some cases, groundwater extraction may be used to lower the water table to dewater the smeared zone, which enables soil venting to remediate highly contaminated soil.

Soil venting and vacuum-enhanced product recovery are remediation technologies that are commonly used in conjunction with groundwater extraction. Vacuum-enhanced product recovery uses product recovery with groundwater extraction and soil venting technologies in the same well(s) to increase the rate of product extraction and to reduce the drawdown. See *Guidance for Design, Installation and Operation of Soil Venting Systems* for more detailed information about soil venting systems. Applying a vacuum to a groundwater extraction well(s) can also increase the rate of groundwater extraction from the well(s) at sites that have a low-yielding well(s).

DNR may require aquifer-restoration techniques other than groundwater extraction if operation of a groundwater extraction system lowers the water table enough to damage a wetland or marsh.

1.3 Permitting and Other Requirements.

Refer to Table 1-1 for more information on DNR rules, guidance documents and agency contacts related to groundwater extraction system design.

1.3.1 LUST, ERP, and Superfund Program Requirements.

Submittal Contents. Recommended Leaking Underground Storage Tank (LUST), Environmental Repair Program (ERP) and Superfund program submittal contents are listed in Subsections 4.5, 5.2 and 5.4.

Wis. Admin. Code NR 141. This code requires preapproval for all groundwater extraction/product recovery wells. Designers must submit an application to the Superfund, ERP, or LUST programs to install a groundwater extraction/product recovery well, which may be part of the work plan for the site. The application must include the information in Subsection 4.2. The same preapproval requirement applies to aquifer test wells (Subsection 3.3). Forms 4400-122 (Soil Boring Log), 4400-113A (Monitoring Well Construction), and 4400-113B (Monitoring Well Development)

Table 1-1

Guidance Documents Related to Groundwater Extraction and Product Recovery

Topic	Pertinent Rules	Guidance Documents[1]	Agency Contact	Reference Section
High Capacity Well Permits	NR 112	None	DNR Water Supply Staff	Subsection 1.3.2
Drilling, Well Construction, and Abandonment	NR 141 and NR 112	None	DNR District ERR Staff	Subsections 1.3.1, 3.3 and 4.2.1.2
Groundwater Treatment and Disposal	Various DNR Rules	Guidance for Treatment Systems[2]	District ERR and/or Wastewater Staff	Subsections 1.1, 1.3.3, 2.4, 3.0 and 5.4
Investigative Wastes	Various DNR Rules	January 14, 1993 Memo[3]	DNR District ERR Staff	Subsections 1.3.1 and 3.0
Free Product Disposal	Various DNR Rules	January 3, 1992 Memo[4]	DNR ERR or Hazardous Waste Staff	Subsection 2.5
Free Product Transportation Off Site	Various DOT Rules	None	DOT Staff	Subsections 1.3.5 and 2.5
Electrical and Building Safety	Various DILHR Rules	DILHR UST/AST Program Letter 10, May 25, 1993[5]	DILHR Staff and/or Local Building Inspectors	Subsections 1.3.4, 2.5, 4.3.1 and 4.4

Notes:

(1) Guidance Documents refers to guidance documents other than this document.

(2) Guidance entitled *Guidance for Treatment Systems for Groundwater and Other Aqueous Waste Streams*

(3) Guidance entitled *General Interim Guidelines for the Management of Investigative Waste.*

(4) Guidance entitled *Waste Classification of Petroleum Products,* included as Attachment One.

(5) Guidance entitled *Design Criteria for Process Equipment Buildings Associated with Environmental Remediation of UST/AST Sites*, included as Attachment 2.

must be completed and submitted in accordance with Chapter NR 141 after well construction is completed. Any well that is no longer in use must be abandoned in accordance with Chapter NR 141, and documentation must be submitted to the DNR on Form 3300-5B.

Investigative Wastes. Drill cuttings should be handled in accordance with DNR guidance on investigative wastes. This guidance is available upon request.

Product Disposal. Product disposal is dependant on the final use and/or disposal option for the product. Petroleum-product disposal and/or recycling is discussed in Attachment 1. DNR will assess regulatory requirements for recovered non-petroleum products on a case-by-case basis.

Federal Free-Product Requirements. 40 CFR 280.64 requires responsible parties at LUST sites to conduct free-product removal in a manner that minimizes the spread of contamination into previously uncontaminated zones by using recovery and disposal techniques appropriate to the hydrogeologic conditions at the site. In addition, the responsible parties must properly treat, discharge or dispose of recovery by-products in compliance with applicable local, state, and federal regulations. This involves preparing and submitting a free-product removal report within 45 days after confirming a discharge to the DNR. The report should include the following information:

- The name of the person(s) responsible for implementing the free-product removal measures;
- The estimated quantity, type, and thickness of free product observed or measured in wells, bore holes and excavations;
- The type of free-product recovery system used;
- The location of any possible discharge from a free-product recovery system (on-site or off-site) during the recovery operation;
- The type of treatment applied, and the effluent quality expected from any discharge;
- The steps that have been taken to obtain necessary permits for any discharge; and
- The chosen disposal/recycling option for the recovered free product.

1.3.2 Water Supply Program Requirements.

NR 112 and High Capacity Well Systems. Chapter NR 112 requires the Bureau of Water Supply's preapproval for high-capacity well systems. A high-capacity well system is an extraction system that produces over 70 gallons per minute (gpm) of groundwater. A system of wells at one site that produces a total of 70 gpm or more is considered a high-capacity system, even if each well pumps less than 70 gpm. A separate application submitted to the Bureau of Water Supply is required for high-capacity well systems. See Chapter NR 112 for a list of required information in an application for a high-capacity well system.

1.3.3 Wastewater Program Requirements.

Groundwater treatment and water disposal are addressed in the *Guidance for Treatment Systems for Groundwater and Other Aqueous Waste Streams*.

1.3.4 Department of Industry, Labor and Human Relations (DILHR) Requirements.

ILHR 10. Designers must follow DILHR codes pertaining to storage tanks for recovered product, electrical safety and building safety. See Attachment 2 for more information on DILHR's requirements.

1.3.5 Department of Transportation Requirements.

Shipping Free Product. The Department of Transportation (DOT) requirements for off-site transport of recovered product are based, in part, on results of flash-point tests.

1.4 Interim Remedial Measures.

Interim remedial measures may be appropriate at certain sites. When appropriate, the DNR encourages responsible parties to implement interim remedies as soon as adequate information is available to design, construct and operate a remediation system. This is especially necessary for free-product removal and source containment/control. The following are examples of situations where interim measures may be warranted.

- A groundwater extraction system is installed in the source area as an interim measure prior to fully completing the groundwater investigation. This type of measure is most common when attempting to hydraulically contain and capture a dissolved-phase plume with high contaminant levels that is moving quickly away from the source area.

- Floating product is hydraulically contained and captured.

- Hydraulic containment is needed to prevent dissolved-phase plume migration towards a receptor, such as a municipal well, or a sensitive natural resource, such as a trout stream.

Interim measures require the same preapprovals and permits as final remedies (See Subsection 1.3).

2.0 Site Characterization.

The following subsections outline site characterization information that is necessary to prepare a remedial design for the system. In many cases, remedial system design (Section 4) can be started before the site characterization is complete. It may be possible to evaluate treatment devices, well design, disposal options, etc. prior to fully completing the site investigation. Because additional plume migration may occur, the validity of the site investigation report decreases with time after its completion.

2.1 Aquifer Characterization.

Important site aquifer characteristics include the following:

- Hydraulic Conductivity. The horizontal hydraulic conductivity is used to estimate the natural migration rate and the groundwater extraction well(s) pumping rate. See Section 3 for a discussion of aquifer testing and Subsection 4.1 for a discussion of plume-capture calculations.

- Aquifer Thickness and Depth. The aquifer thickness is needed to determine transmisivity from the hydraulic conductivity estimate for plume capture (Subsection 4.1). The plume depth within the aquifer is also needed to establish the screened interval when designing a groundwater extraction well or trench system (Subsection 4.2). A boring should be drilled to verify the hydrogeologic conditions in the screened interval prior to installing an extraction well.

  At small sites with very thick aquifers (over 50 feet of saturated thickness), a boring does not need to extend to the base of the aquifer IF a piezometer indicates that the plume does not extend to the base of the aquifer. Subsection 4.1 discusses estimating an effective aquifer thickness for plume capture in thick aquifers.

  If a deep boring is drilled through a highly-contaminated zone, drilling techniques may have to be modified to limit the potential contaminant movement into previously clean zones. Temporary well casings or other preventative measures may be necessary in some situations.

- Transmisivity. The following information is used to determine plume capture: the saturated-aquifer thickness (or effective thickness, if appropriate) multiplied by the horizontal hydraulic conductivity equals transmisivity. See Subsection 4.1 for more information.

- Natural Horizontal Groundwater Flow Direction and Gradient. The direction of groundwater flow and hydraulic gradient are necessary for plume-capture calculations (See Subsection 4.1). If there is a potential for time-varying natural groundwater flow directions, the plume-capture calculations can provide misleading results. It is advisable to prepare a minimum of three water-table maps of the site with a minimum of one month (preferably two months) between each set of readings to verify the natural direction of groundwater flow. If there is a potential for significant plume migration, it may be better to quickly address contamination problems instead of waiting to accumulate water-table data. It is recommended that designers evaluate of the advantages of collecting more data versus the advantage of rapidly capturing the plume to avoid significant migration.

The direction of groundwater flow is typically the same as the downgradient slope of the water table, however, the groundwater flow may vary in anisotropic conditions. If iso-concentration maps suggest that the migration direction is not directly downgradient, the remediation system designer should consider the potential for future migration to differ from the groundwater gradient.

- Water-Table Fluctuations. Fluctuations of the water table are evaluated to determine the screened interval of wells and trenches. This is important at sites with floating product, so that the floating product can enter the well screen. It is also important at other sites to ensure that the wells are installed deep enough to provide the capacity needed for plume capture under a seasonal-low water table.

- Storage Coefficient or Specific Yield. The storage coefficient or specific yield is calculated and reported if pumping tests are performed (Section 3).

- Grain-Size Distribution. The well-screen slot-size is determined by the grain size of the filter pack, which is determined by the grain size of the formation adjacent to the screen. A boring should be drilled to obtain the grain-size sample(s) to determine the groundwater extraction-well screen-slot size. If it is apparent during the investigation that groundwater extraction is needed, a deep boring should be part of the site investigation. Subsection 4.2.1.2 discusses sizing the filter pack and slot size.

2.2 Geologic Characterization.

A geologic characterization assesses the interaction of aquifers and aquitards that may be present at a site. The important site geology characteristics are as follows:

- Geologic Unit Below the Aquifer. The importance of characterizing the unit below the aquifer varies greatly from site to site. Guidelines to follow include:

  It is necessary to assess the vertical component of the hydraulic gradient with a well nest that includes at least one piezometer if there is the potential for vertical migration to lower geologic units.

  If the contaminant plume does not reach the base of the aquifer, the underlying unit is relatively unimportant and may be estimated for depth only. In this case, the "clean" water under the plume should be characterized with at least one piezometer.

If the contamination extends to the base of the aquifer, designers should assess the ability of the underlying unit to restrict the movement of the contamination (less-permeable unit) or its ability to transmit contaminants (more-permeable unit). Characteristics of underlying hydrogeologic units to assess include:

- hydraulic conductivity (vertical if less-permeable, or both vertical and horizontal if high-permeable);
- secondary permeability; and
- vertical gradients.

If there is a potential for DNAPL at the site, designers should accurately define and characterize the depth of the aquifer base. A large volume of DNAPL may flow in a direction different than the groundwater flow if the surface of the confining layer slopes in a different direction than the groundwater gradient. Therefore, the topography of the confining layer surface should be determined.

- Geologic Unit Above the Aquifer. If the aquifer is confined, the overlying confining layer should be characterized for vertical hydraulic conductivity and the gradient across the unit.

- Soil Description. A hydrogeologist that meets the definition in NR 500.03 (64) (or NR 600.03 (98)) should prepare the boring logs. Soil description should include the following information:

  - Approximate percentages of major and minor grain-size constituents. Note: Terms such as "and," "some," "little," "trace," etc. are acceptable if percentages they represent are defined;

  - Color and Munsell Color;

  - Geologic origin;

  - Description of moisture content (e.g., dry, moist, wet);

  - Any visual presence of secondary permeability;

  - Voids or layering;

  - Pertinent field observations such as odor;

  - Description and notation of any product smearing evidence. Hydrogeologists should note the depths carefully because depth of smearing is evidence of past-aquifer water-level variations.

2.3 Extent of Contamination.

A definition of the areal and vertical extent of contamination is necessary for plume-capture calculations (See Subsection 4.1). The vertical extent is also necessary for well design (See Subsection 4.2).

Soil samples collected from soil borings should be field screened for VOC measurements at sites where VOC contamination is suspected. Field screening may consist of the following:

Headspace analysis using:

- Photoionization (PID);
- Flame ionization detector (FID);
- Field gas chromatograph (GC); or
- Lab in a Bag Method (Robbins, 1989).

Other pertinent field observations such as odor should be included in the site investigation report, and any evidence of product smearing should be noted and described (product smearing means a free-phase product coating on soil particles).

2.4 Contaminant Chemistry.

Treatment and/or disposal systems must be designed for the extraction rate and types and concentrations of the site contaminants. See the *Guidance for Treatment Systems for Groundwater and Other Aqueous Waste Streams* for a detailed discussion of groundwater treatment.

Seals, bearings, pitless adaptor/units, and motor leads in pumps designed for clean water use are often not compatible with contaminants, so special pumps may be required. Designers should assess well materials and equipment for contaminant compatibility before using them in the extraction system.

2.5 Floating Product or DNAPL.

If a floating, recoverable product layer is present at a site, designers must insure that the well-screen interval intersects the product layer under static conditions and all potential-pumping levels (see Subsection 4.2).

In some cases, only a small volume of floating product is present at a site. In this case, the designer should evaluate whether or not product recovery by pumping is necessary, or if other means (such as evaporation by soil venting) can efficiently extract the product. There are several ways to estimate the volume of floating product (Hughes 1988, Testa 1989, and Farr, 1990). Kemblowski (1990) also discusses fluctuating product thickness that is caused by fluctuating water tables. If the volume of product is too small to warrant extraction using product recovery techniques, an estimate of the product volume should accompany a justification in the work plan, along with the alternative approach for removing the free product.

Designers should carefully choose equipment if ignitable floating product is present at a site. Intrinsically-safe or explosion-proof equipment is typically required when ignitable contaminants are present. See Attachment 2 for more information on equipment selection.

The British Thermal Unit (BTU) content of the recovered petroleum product may be needed to assess petroleum product-disposal options. BTU content may affect the ability to recycle the product as a fuel because too low a BTU content may make it too costly to recycle the product for fuel usage.

Flash point is used to characterize the product for shipping the recovered product off-site in accordance with DOT regulations.

2.6 Other Site-Specific Characteristics.

Other site characteristics that should be included in hydrogeologic investigations include, but are not limited to, the following:

- Presence of nearby wetlands or surface water bodies;
- A fractured-aquifer matrix;
- Structures that affect groundwater and/or floating product or DNAPL flow;
- High-capacity wells that influence natural-flow patterns; and
- Other wells which might be impacted.

3.0 Aquifer Testing.

Aquifer testing is necessary to estimate the hydraulic conductivity or transmisivity for plume capture calculations. In some cases, the hydraulic conductivity tests conducted during the site investigation provide sufficient data for remedial design. In other cases, a pumping test prior to remedial design may be necessary to accurately estimate the rate of groundwater pumping that is needed to capture the plume.

In some situations, aquifer testing techniques such as a slug tests, bail-down tests, and grain-size methods provide sufficiently accurate hydraulic conductivity estimates. However, these techniques may not be sufficiently accurate for design purposes.

The following is a list of aquifer tests in decreasing order of accuracy:

- Long duration (multi-day) constant rate pumping tests;
- Short duration (less than eight hours) step drawdown tests;
- Bail-down and slug tests; or
- Permeability calculations based on grain-size analysis.

Some suggested guidelines when testing aquifers include the following:

- A plume in sand or gravel that is hundreds of feet long and over 100 feet wide is a major groundwater extraction project; therefore, a pumping test is probably necessary.
- In silt and clay soils, a likely pumping rate is several gpm or less. A bail-down test from each well generally provides sufficient data for evaluating design, treatment, and/or disposal options. Although a pumping test more clearly defines an aquifer, it may be more cost effective to oversize the groundwater extraction/treatment system and delay a pumping test until after the system installation, provided that it is relatively inexpensive to oversize the groundwater treatment system.
- A pumping test is probably needed prior to designing groundwater extraction systems that are likely to produce more than 50 gpm, but is probably not necessary for systems that are likely to operate at less than 5 gpm. If the system is likely to produce in between 5 and 50 GPM, designers should assess site-specific factors such as water disposal options, treatment needs, etc. to determine what level of accuracy is needed for an aquifer test.

A careful evaluation of the costs and benefits of a pumping test may be warranted. If a pumping test is not proposed at a site, the hydrogeologist should include an evaluation of the aquifer-testing data quality in the report to justify the exclusion of a pumping test.

If a number of aquifer-testing results are available, the geometric mean of the results should be used to calculate the average hydraulic conductivity (Domenico and Schwartz, 1990; page 67). If multiple hydrogeologic units are present, designers should calculate the geometric mean for each hydrogeologic unit, not a single, overall site average. If some results have a higher degree of certainty, designers should NOT use the results that are less certain in the calculation.

> Example: If both pumping test results and Hazen method results are available, the Hazen method results should not be used when calculating the geometric mean due to the higher level of uncertainty.

The groundwater discharged during an aquifer test or well development should be sampled and chemically analyzed for contaminants and other parameters that may affect the treatment system and/or disposal options (See *Guidance for Treatment Systems for Groundwater and Other Aqueous Waste Streams* for more information).

Water that is produced as part of aquifer testing must be handled in accordance with DNR rules applicable to investigative wastes. Portable, low-volume air strippers or carbon filters may be used as treatment for water that is produced by pumping tests. Preapproval is necessary by the Wastewater program if discharging to a storm sewer or surface water body. In some cases, a POTW will accept untreated pumping test water without significant costs. The POTW will probably require test results from the well prior to approving the discharge. It may require parameters in addition to LUST, ERP, or Superfund program requirements, such as BOD_5 or suspended solids. The local POTW should be contacted to determine necessary analytical requirements.

Designers should evaluate the means and costs of water disposal when determining which aquifer characterization method to use.

3.1 Hydraulic Conductivity Estimates Based on Grain-Size Analysis.

A mathematical determination of the hydraulic conductivity based on the grain size is rarely appropriate for designing a groundwater extraction system. A grain-size test may be used in unconsolidated material to corroborate other tests. The reasons for poor performance of this test include the following:

- There are a number of methods available (Shepherd, 1989, Masch and Denny, 1966, Hazen method described in Freeze and Cherry, 1979 and Fetter, 1988), but no single test is proven to be best under all conditions.

- Most methods are only applicable to sand. Note: The Hazen Method is only valid for a grain size of $0.1 < D_{10} < 3.0$ mm, the Masch and Denny method is limited to samples of unconsolidated sand.

- The samples that are collected for grain-size analysis are from very small discrete locations. Often, only one to three samples are tested; therefore, only a few discrete parts of the site are used to estimate the overall site hydraulic conductivity and transmisivity.

- Some methods disregard soil density, porosity, grain roundness, etc.

- Only groundwater flow through primary porosity in soil is evaluated in a grain-size test, if there is flow-through secondary porosity – such as fractures in till – the conventional tests are invalid.

- The tests are not appropriate for bedrock.

3.2 Bail-Down and Slug Tests.

Bail-down (water-table wells and piezometers) or slug tests (piezometers) provide better hydraulic conductivity estimates than grain-size analyses.

> Note: For purposes of this document, a bail-down test is a test that instantaneously extracts or withdraws a volume of water or a slug from the well, and a slug test is a test that instantaneously injects a solid slug into the well.
>
> Slug tests are conducted in piezometers AND ONLY IN PIEZOMETERS. A slug test in a water-table well will force water into the unsaturated filter pack and possibly the unsaturated native soils, increasing the length of submerged screen. Changing the length of the submerged screen during the test, makes the test invalid (Bouwer, 1989).

Most general hydrogeology texts describe these tests and provide a number of references. Selected references include Cooper, et. al. (1967), Bouwer and Rice (1976), and Bouwer (1989); there also are many other articles on these tests in various publications.

Bail-down or slug tests may not provide the most accurate results for the following reasons:

- Only the part of the aquifer immediately adjacent to the filter pack and screen is evaluated.

- When testing water-table wells, only the uppermost part of the aquifer is tested. More representative results are obtained from wells which reflect an overall average of the aquifer.

- If tests are conducted using piezometers, they only test a very small part of the aquifer in the vertical dimension because piezometer screens are usually only 5 feet long and the sand pack is 7 to 8 feet long.

- If there is flow in secondary porosity channels, the wells may not intersect the channels or fractures and would only evaluate the primary permeability. If a fracture is intersected by the well, the interpretation could also be inaccurate because the assumptions in the conventional methods are violated (Karasaki, 1988).

- If the wells are not adequately developed, they will not yield meaningful results. Smearing of the bore hole during drilling will cause the well to reflect an artificially low permeability.

  > Note: Because wells that are not developed to Chapter

NR 141 standards typically do not provide accurate hydraulic conductivity estimates with slug or bail-down tests, these wells should be redeveloped prior to aquifer testing.

- High-permeable aquifers often yield artificially low estimates with slug/bail-down tests because the injection/extraction rate relative to the rate of the induced inflow/outflow from the aquifer is not instantaneous.

- If the filter pack is less permeable than the native soil, the calculated hydraulic conductivity is artificially low because the test measures the hydraulic conductivity of the filter pack. Chapter NR 141 specifies the size of the filter pack and slot size in monitoring wells. A screen slot size that is too small can also limit the groundwater flow into a well lowering the hydraulic conductivity estimate in high-permeable aquifers.

3.3 Pumping Tests.

A pumping test extracts groundwater at a constant rate for a number of hours, and a step drawdown test varies the pumping rate over time. These tests are used to calculate the aquifer transmisivity and specific yield or storage coefficient. Most general hydrogeology texts cover the basics of pumping tests; Kruseman and de Ridder (1990) is an excellent reference.

In some cases, an additional monitoring well or aquifer-test well is necessary to perform a pumping test. A pumping test can be performed in an aquifer-test well constructed for the pumping test, a groundwater extraction well, or an oversized (4-inch) monitoring well. An aquifer-test well should be evaluated for entrance velocity (Subsection 4.2.1.2) prior to installing the well. A wire wrapped screen may be necessary in high-permeable aquifers to reduce entrance velocity. In this case incrustation due to a high entrance velocity is not an issue because of limited pumping duration, but flow restriction through too small a slot size could occur.

A longer well screen than normally used for a monitoring well may also be necessary to achieve the desired drawdown and flow rate during the pumping test. If the aquifer-test well is upgradient of the source and within the same geologic unit, it may produce clean water. Disposing of clean water from a pumping test is much easier than contaminated water. This may be a factor when planning the duration and pumping rate for a test. Aquifer-test wells require preapproval under NR 141.

General considerations for pumping tests include the following:

- A method that accounts for partial penetration and/or unconfined conditions is appropriate in most aquifer-decontamination projects. During a pumping test, the groundwater below a partially penetrating extraction well is relatively stagnant and does not "flow" during the test, therefore, this portion of the aquifer is not "tested" during the pumping test. Methods that assume a fully penetrating well could result in a transmisivity estimate that is artificially low.

  Driscoll (1986) indicates that partial penetration effects are minimized at a distance (from the extraction well) that is twice the aquifer thickness. Therefore, methods based on fully penetrating wells (including the Jacob straight line method) can be used on data from monitoring wells that are a significant distance from the extraction well. If the Jacob straight line method is used, the calculated u value should be less than 0.05 (Driscoll, 1986).

N. Boulton and S. Neuman have each published a number of articles about aquifer testing in unconfined conditions. Fetter (1988) lists a number of references related to aquifer testing (pages 209 to 212) including most of those by Boulton and Neuman.

- The classic pumping test for a water-table aquifer is a 72-hour test. Confined aquifers may need a 24-hour test. At some small sites, a low-capacity test (less than 10 gpm) for a shorter period of time (8 to 24 hours) may be sufficient.

  The length of the pumping test may need to be modified if the hydrogeologist conducting the pumping test determines that a different length of time for the test is necessary, based on initial test data. If early test data suggests that the drawdown in an unconfined aquifer has stabilized, the pumping test should continue long enough to ascertain that a delayed yield or slow drainage effect is not influencing the interpretation.

- Water-level measurements should be collected at all available measuring points. Even distant points that are outside the radius of influence provide data on background water-level fluctuations during the test.

  > Note: Hydrogeologists should collect water and product level measurements in wells with floating product. However, wells with floating product should not be used for pumping test evaluation, unless there is a shortage of wells at the site. Because the dynamics of multi-phase fluid flow into and out of a well with floating product may introduce error, these monitoring wells may provide misleading results. If wells with floating product are used, the density of the product should be estimated to calculate the equivalent head in the well.

- In all cases, recovery data for a pumping test is collected and evaluated, especially at the groundwater extraction well.

- Casing storage can influence early drawdown data in large-diameter wells that are installed in relatively impermeable aquifers. See Kruseman and de Ridder (1990) and/or Driscoll (1986).

In some cases, a short step-drawdown test is a viable alternative to a full-scale pumping test. Small-diameter electric submersible pumps that fit in 2-inch wells that can be used for step-drawdown tests are available. If a 4-inch monitoring well is used at the site, a higher capacity step-drawdown test can be conducted.

4.0 Design and Installation of a Groundwater Extraction System.

Groundwater extraction and product-recovery systems may consist of a single well, include multiple low-capacity wells, or use a trench system. It may be appropriate to install a groundwater extraction or extraction/product-recovery well in the source area to minimize free-product migration, as well as install a groundwater extraction well further downgradient to capture dissolved-phase contaminants. No specific extraction system design is appropriate for all conditions; a system should be tailored to meet site-specific conditions and contaminants.

4.1 Capture Zone.

Groundwater extraction systems are designed to contain and remove contaminated groundwater from the aquifer. The size of the plume which the extraction system will be designed to extract varies from site to site depending upon factors such as aquifer conditions, degree of contamination, distribution of contamination, and the location of receptors. A groundwater extraction system may operate as a form of source control, or as aquifer restoration, or for both purposes. If free product is present at a site, the system may consist of two recovery wells; one for free-product recovery in the source area, and one downgradient to capture a dissolved plume.

A larger capture zone, over and above the zone of contamination, is sometimes warranted if there is a low level of confidence in the distribution of contamination or the aquifer-testing results.

Some sites have primarily radial migration away from the source, other sites have a lineal plume extending from the source. The methods of evaluating capture vary depending on the plume configuration. In general, most remediation systems at smaller sites can be modeled if one of these two plume configurations match the following descriptions:

- Sites With High Hydraulic Conductivity and High Natural Groundwater Migration. These sites typically consist of a long, narrow plume that extends downgradient from the source area. Contaminant transport at these sites is primarily controlled by advection. Diffusion and dispersion are only minor transport processes. Capture zones are calculated based on three parameters: pumping rate, natural gradient, and transmisivity.

  Dispersion allows contaminants to travel along routes other than streamlines. The capture zone should be designed to capture a larger area than the known zone of contamination. The width of the extraction system's capture zone should be 15 to 25 percent (or more) wider in high-permeable aquifers and 30 to 50 percent (or more) wider in moderate to low-permeable aquifers.

  The following two methods, analytical and mathematical, are used to determine the capture zone:

  - Analytical. A very simple two-dimensional model that is appropriate for simple sites with a single extraction well is described by Todd (1980, pages 121 to 123). An example of this method is included in Attachment 3. Another method is described in Javandel and Tsang (1986), and in Fetter (1993). Several hydrogeology texts, such as Domenico and Schwartz (1990), also describe similar mathematical solutions for the capture zone. Other analytical methods for more complicated site conditions using advanced mathematics are presented by Strack (1989). Grubb (1993) applies the same mathematical principles that are used by Strack for simple site conditions. Both Strack and Grubb provide methods for confined and unconfined aquifers.

If there are known seasonal fluctuations in the groundwater gradient, the capture zone should be calculated under all known groundwater gradients to verify that contaminant capture will occur.

— Computer. This method is appropriate for sites with multiple extraction wells, an extraction trench, or with sites that experience significant changes in groundwater-flow patterns due to seasonal effects or natural infiltration effects. There are many two-dimensional modeling programs available that can quickly and inexpensively evaluate groundwater flow to extraction well(s). At more complex sites, three-dimensional models may be needed, however, cost will often preclude their use at simple or small sites. The extraction system should be modeled under differing natural gradients to assure that the extraction well(s) is in the optimal location and has a sufficient pumping rate under all seasonal effects.

> Note: The DNR does not endorse or approve groundwater modeling programs. It is the responsibility of the remediation system designer to use a model that will provide correct and meaningful results. The designer is expected to provide sufficient documentation for DNR model review.

- Sites With Low Hydraulic Conductivity and Minimal, Natural Groundwater Migration. If the site has very low-permeable soils, it is likely that contaminants have migrated radially away from the source primarily due to diffusion and not advection. A centralized extraction system in the source area may be used if contaminants have migrated a short distance or mostly radially away from the source area.

  In these cases, the remediation system designer needs to design a system with a cone of depression that establishes an inward gradient at the perimeter of the contamination zone. The DNR does not specify a minimum inward gradient; however, a minimum inward gradient of 0.01, or more, is recommended. The system may be designed based on computer modeling (see computer information above) or by an analytical method. An analytical example of this method based on Todd (1980) is included in Attachment 4. Other analytical solutions are also acceptable.

At large sites with low anticipated pumping rates, the designer should consider calculating the time of travel from the perimeter of contamination to the extraction points. This estimate is a measure of the time that is necessary to extract one pore volume from the limits of contamination. If a long period of time is necessary to extract one pore volume, then it is likely that groundwater restoration will take a long time.

The modeling methods above are typically based on two-dimensional capture zone calculations. Because the methods are two-dimensional, the estimated pumping rate can be overestimated in very thick aquifers if the total aquifer thickness is used in the calculations, and water is only extracted from the upper portion of the aquifer. When calculating the extraction rate from a partially-penetrating well in an aquifer that is very thick relative to plume depth, it may be appropriate to assume an "effective" aquifer thickness that is less than the full thickness.

In the case of a partially penetrating groundwater extraction well installed at the water table, designers can assume an effective aquifer thickness that is the sum of one-half of the plume-capture zone width, plus the screen length. Partially penetrating groundwater extraction wells screened below the water table (confined aquifers and submerged plumes in unconfined aquifers) may have an assumed effective-aquifer thickness that is equal to the capture zone width plus the screen length. This method of estimating an effective-aquifer thickness is not absolutely correct in mathematical terms, but it should provide reasonable results, assuming isotropic conditions. This approach is based on simplistic assumptions; other scientifically valid methods based on known site-specific conditions may also be used.

After the flow rate is determined, the designer should predict the drawdown in the well to determine if it is reasonable. If the well is a partially penetrating well, a correction for partial penetration should also be made. Attachment 4 includes sample calculations for drawdown and partial penetration. Also, see the discussion of maximum drawdown recommendations for extraction wells in Subsection 4.2.

If a single well does not deliver the capacity that is necessary for plume capture, designers should consider other alternatives to assure that the extraction system will deliver the desired capacity. There are a number of options that can be used in those situations, including:

- Multiple extraction wells can be used with reduced-flow rates on a per well basis, which reduces drawdown in each well. When multiple wells are used, superposition can be used to estimate the drawdown in each well.

- A trench system may be used instead of a well.

- The length of the screen can be increased. The system designer should carefully consider the costs associated with pumping, treating, and disposing of clean water that is pumped from under the plume if this option is considered. This option may seem cost-effective because it moves more water at a minimal cost, initially. BUT, in some cases, the treatment and disposal costs for pumping clean water for many years make this a high-cost option.

The modeling methods described above are only applicable to flow-through primary porosity. If flow-through secondary porosity (fractured flow) affects contaminant migration, the consulting hydrogeologist should propose an alternate means of locating groundwater extraction systems based on the apparent direction of contaminant flow and distribution.

After installation and start-up of the groundwater extraction system, designers should periodically prepare water-table maps that depict the capture zone. See Subsection 5.3 for more information on groundwater maps.

4.2 Well or Trench Design.

A groundwater extraction system in high-permeable soils typically consists of a drilled well(s), and a groundwater extraction system in low-permeable soils typically consists of a trench system(s). There are no specific conditions that determine the use of a trench instead of a well. If the desired groundwater extraction rate cannot be achieved with less than about 10 feet of drawdown in a water-table well, a single well is insufficient and a trench or multiple wells are needed. If floating product is present, the drawdown should be limited to no more than 5 to 6 feet to limit product smearing on soils. There is no recommended maximum drawdown in wells that are installed in confined aquifers or that pump from submerged plumes. Generally, at least 5 feet of screen should be in the aquifer under pumping conditions.

> Note: Product smearing occurs when the soil particles are coated with free product and the interstitial void spaces between the particles are partially filled with free product.

A trench system may be difficult or impossible to install if the trench does not stay open long enough for pipe installation and backfilling, and installing a very deep trench may be impractical. If a single well is insufficient and a trench system cannot be installed, multiple low-capacity wells may be necessary.

4.2.1 Drilled Wells.

If the groundwater extraction well is screened (or open hole in bedrock) in a confined unit, the well should be designed to prevent contaminants from flowing upward through the annular space to uncontaminated zones. In some cases, a temporary (or permanent) casing that seals off upper, "clean," high-permeable zones during drilling is necessary. This may preclude the use of some drilling methods (hollow-stem auger and bucket auger) at some confined-aquifer sites.

4.2.1.1 Drilling Method.

There are many site factors that determine the method of drilling. The system designer should use a method that results in proper construction of an efficient extraction system. Driscoll (1986) is an excellent reference for drilling methods. For shallow, large-diameter wells in low-hydraulic conductivity environments, a large bore hole may be needed. The following is a brief summary of the commonly used drilling methods:

- <u>Cable Tool.</u> Cable drilling offers great flexibility. The well can be installed with a natural-filter pack when the casing-pullback method is used, or with an artificial-filter pack when a large-diameter temporary casing is used. Because there is minimal smearing (relative to hollow-stem augers) and no filter cake against the bore-hole wall, well development time is reduced. The disadvantage of cable drilling is the large amount of time it takes to install a well.

> Note: Many cable drillers use arc welding and a cutting torch. Drillers should be warned of any ignitable contaminants or the presence of a floating-product layer. If these conditions exist, the driller should use a threaded and coupled pipe.

- Hollow-Stem Auger. In some low-flow applications, a 6.25-inch inside-diameter hollow-stem auger can be used to install a 4-inch well constructed of polyvinyl chloride (PVC). Some drilling contractors have 10.25- or 12.25-inch inside-diameter hollow-stem augers that can be used for larger wells. Advantages include speed and the ability to collect split-spoon samples and conduct field headspace tests.

  The disadvantage of the method is that large-diameter augers can only penetrate limited depths. There can be considerable smearing of the bore-hole wall in stratified formations, especially if those formations are loose or soft (as exhibited by low-blow count N values) because the finer-grained soil cuttings may be pressed into the coarser-grained layers. The smearing effect is less critical in clean outwash deposits. In most cases, flush threads should be used for screen and casing.

- Mud and Clear-Water Rotary. Mud rotary is a common method for drilling water-supply wells. Drilling mud should not be added if the hole stays open with clear water. Wells drilled with this method need significant development to remove the filter cake from the bore-hole wall especially in high-permeable formations. The main advantages of this method are speed and the availability of drilling rigs.

- Bucket Auger. When drilling in fine-grained soils that stay open, a large-diameter well can be installed by using a bucket auger. The bucket auger is a good choice if the design bore-hole diameter exceeds a couple of feet and the well is fairly deep. If the hole will not stay open, a bucket auger is not a good choice.

Other methods, such as air rotary or rotasonic, may be appropriate in unique situations such as in bedrock. In all cases, drill cuttings must be handled in accordance with the DNR rules that are applicable to investigative wastes.

4.2.1.2 Filter Pack, Screen, Casing, and Well Development.

Filter Pack and Well Screen. If designers use a filter pack, it should be appropriately sized to the native soils. An artificial-filter pack extends a minimum of 2 feet above the top of the screen. If a long screen in a loose formation is used, the filter pack should extend a minimum of 5 feet above the top of the screen because a large amount of filter pack and native soil can be removed from the bore hole during development. If sufficient materials are removed, the filter pack and annular space seal can collapse to the top of the screen.

The well screen may be constructed of PVC, low-carbon steel, galvanized steel, or stainless steel. In unusual-site conditions, other materials may be appropriate. The remediation system designer should consider the duration of the project when selecting screen material. The screen manufacturer may provide advice on material characteristics to limit or prevent corrosion, incrustation and contaminant compatibility. Non-reactive materials need to be used in extraction well design. In unusual cases, such as very deep wells, the physical strength of the screen should also be evaluated in consultation with the screen manufacturer.

The slot size of the screen should be sized to the filter pack (or natural pack if used). See Chapter NR 112 for a discussion of filter pack and screen specifications. If a natural-filter pack is used, refer to page 435 in Driscoll (1986) for a discussion of screen-slot size. A well with a screen that has slots that are too large and/or a filter pack that is too coarse may pump sand. If stratified conditions exist, a relatively fine-grained layer should be used for selecting the filter pack and the well screen-slot size. On-site screen manufacturing, such as torch cut slots and drilled perforations, and on-site slotting by saw cutting are not acceptable.

The screen diameter is usually a function of the type of pump(s) (Subsection 4.3), sensors (Subsection 4.4, Control Panel) and possibly a shroud (Subsection 4.4) that are installed in the well. Only in rare cases is a screen diameter controlled by factors other than the pumping equipment dimensions.

If there is a possibility that a floating product or DNAPL recovery pump installation may be needed in the well, the well-screen diameter should be sufficient for a two-pump system (Subsection 4.3). In some cases, a recoverable floating-product layer forms after pumping begins, even though it did not appear during the investigation. If there are unusually high dissolved-contaminant concentrations, the designer should use a well with a sufficient diameter to also hold a product recovery pump, in case it is later determined that a product pump is needed.

If floating-product recovery is initially planned, or there is evidence that floating product may be drawn into the well, the top of the screen should be above the seasonal-high static water table. If recoverable floating product is unlikely to be present, the top of the screen should be set at or above the top of the plume.

The base of the screen should be set so that the entire length of the screen extends through the entire contamination zone. In general, it is a good practice to maintain at least 5 feet of well screen within the aquifer under pumping conditions. In some cases, the base of the screen is set slightly below the plume to maintain at least 5 feet of screen below the pumping level.

If multiple high-permeable zones are present and contaminated, THE SCREEN MUST NOT CROSS CONNECT HIGH-PERMEABLE ZONES THAT ARE SEPARATED BY LOW-PERMEABLE ZONES. In these cases, designers should use separate wells for each high-permeable zone because a single well in this situation would be an artificial conduit to vertical-contaminant flow during periods when the well is not pumped.

Screen incrustation can occur if the entrance velocity is greater than 0.1 feet per second (Driscoll, 1986). Driscoll (1986) contains example calculations for determining entrance velocity. Most well-screen manufacturers will provide the open area per lineal foot of screen for the calculations. Designers should use the estimated length of screen under static, seasonal-low water-table conditions, minus the anticipated drawdown, when estimating the length of screen for calculations. If the design calculations indicate that entrance velocity is greater than 0.1 feet per second, other screen types or larger-diameter well(s) may be used. If the calculated entrance velocity is significantly above 0.1 feet per second, the well may not produce the desired extraction rate. Attachment 4 discusses estimating drawdown.

A bottom plate must be used on all well screens. If it is possible to recover any DNAPL, the base of the screened portion of the well should be designed so that as much DNAPL is recovered as possible.

Bedrock Wells. Well installation with open hole is acceptable if the extraction well is in bedrock, instead of constructing the well with a filter pack and screen. An open hole should not cross connect high-permeable zones separated by a low-permeable zone(s).

Casing. The casing may be PVC (when PVC screens are used) or steel pipe. In some rare cases with unusual-site conditions, stainless steel casing or other materials may be used. If the well casing is less than 8 inches in diameter, the casing should be schedule 40. If the well diameter is equal to or greater than 8 inches, see Chapter NR 112 for casing wall thickness specifications. If unusual conditions warrant using stainless steel casing, the DNR project manager may allow a thinner wall thickness.

Development. After the well is completed, the well should be developed. Driscoll (1986) provides an excellent discussion of well development methods. Development over and above Chapter NR 141 requirements is encouraged to provide an efficient extraction well.

Any grout in the annular seal should be allowed to set for a minimum of 12 hours prior to well development. Also, significant quantities of water and fines can be produced by some development methods. The system designer should plan for disposal of development water before installing the well(s).

4.2.2 Trench Systems.

Trench systems are only used to install groundwater extraction systems if the water table is very shallow and the soil has low permeability. They are typically installed by a backhoe. The purpose of the trench is to create a high-permeable channel through the native soil to extract more groundwater than a well. The saturated zone of the trench should be backfilled with a high-permeable material, such as coarse sand or gravel. If the trench is very long, a perforated pipe or well screen should be installed horizontally in the base of the trench to conduct water to an extraction well or sump.

The unsaturated zone of the trench should be backfilled with the spoils that were originally excavated from the trench. In some cases, a geo-textile can be installed above the coarse gravel and below the backfill. If floating product is present, the high-permeable material should extend one or more feet above the seasonal high water table to assure that the floating product will not rise into the native fine-grained backfill.

Designers should install a well or sump — while backfilling the trench — in the high-permeable backfill material in the trench. The well should be installed as plumb as possible. Often, the well screen and casing are assembled prior to placement in the excavation, then the screen/casing assembly is hung by the backhoe into the excavation. Lastly, rope is used to support the top of the screen/casing assembly in the vertical position during backfilling.

Note: Screen and casing specifications for the well or sump are the same as those described above in Subsection 4.2.1.2.

A backhoe can be used to install a groundwater extraction well at sites with low permeability and a high-water table. The well can be installed in a former buried storage tank excavation, if appropriate. In this case, well construction is similar to a trench system.

4.3 Pump Selection.

4.3.1 Groundwater Extraction Pumps.

Electric submersible pumps are the groundwater extraction pumps usually used at contaminated sites. In lower flow-rate applications, alternative pumps such as pneumatic pumps are also used.

Pump materials should be compatible with the contaminants present at the site. The pumps should be constructed of stainless steel, and the motor leads, seals, and bearings should be made of materials that are compatible with the site contaminants.

In general, submersible pumps do not have to be explosion-proof because the pump motor is below the intake of the pump (therefore the pump motor is always submerged and is isolated from the contaminant vapors). Electrical sump pumps that have a motor above the pump inlet should be explosion-proof; see Attachment 2 for more information.

Designers should select the pump based on the desired pumping rate and the hydraulic head. Calculation of the total head is the total of:

- the elevation to which the water is pumped, minus the pumping elevation;
- the total head loss due to pipe friction; and
- head loss from all other fittings and devices such as flow meters, valves and possibly the treatment system.

The pump should be selected based on performance curves provided by pump manufacturers.

If a pump that has excess capacity is used, a throttle valve may be added to the line near the treatment system to artificially create more head. If a throttle valve is used, care is needed to avoid burning out the pump by creating too much restriction to groundwater flow. A pressure gauge marked with the maximum pressure (from manufacturers data minus elevation head) may also be installed in the line near the throttle valve to prevent accidental damage to the pump. Restricting flow in this manner is not recommended for long-term operation; it is only appropriate for temporary operational needs. Other devices to prevent over pumping are discussed in Subsection 4.4 under control panels.

Electrical connections to the pumps must be designed to specifications that are acceptable to the local electrical inspector. The wire insulation to the pump motor should be compatible with the site contaminants. If the contaminants are ignitable, the local electrical inspector may require an explosion-proof junction box mounted on the outside of the well casing.

Compressed air lines that are used for pneumatic pumps can freeze up in cold weather, and they should be protected from subfreezing conditions if practical. An automatic water trap should be installed on the air line to assure that any water that condenses in compressed air lines does not enter the pump or the pump controller. If the air compressor has a receiver (air tank), installing an automatic water trap is recommended to drain condensate from the receiver.

4.3.2 Floating-Product and DNAPL Pumping Systems.

Floating-product and DNAPL recovery pumps are designed or controlled to only pump free product, and the pumps may be electric or pneumatic. The selection of a pumping system is based on the following information:

- Range of Water-Table Fluctuations (Excluding DNAPL Pumps). If the water table fluctuates more than 0.5 feet per week on a regular basis, the pump should be able to operate under changing water-table conditions. Designers should use pumps that have a float mechanism that automatically adjusts to changing water levels, or that use a filter that allows product (but not water) to flow into the pump inlet. Pumps that depend on a preset elevation of product are often set at the wrong elevation.

- Frequency of Maintenance/Inspection. Pumping systems that require frequent maintenance or frequent elevation changes are very expensive in the long-term because of the extra site visits that are required.

- Potential for Failure. The pumping or DNAPL system should be operated independently of the groundwater extraction pumping system. This ensures that groundwater extraction continues and plume capture and containment is maintained if there is an equipment failure.

  Note: A single control panel for both systems is acceptable.

- Characteristics of Failure. Some pump systems can cause catastrophic failures in other associated equipment. For example, a pneumatic pump or control unit failure can cause over-pressurization and other equipment failure. If designers use pneumatic pumps, it is very important that the product tank is properly vented and the air compressor has a reliable pressure regulator.

- Volume of Product to Pump. In almost all cases, a low-capacity product pump is sufficient. For example, at only 0.1 gpm the pump can still recover over 4,000 gallons per month.

- DNAPL. In the rare case where DNAPL is recoverable, or anticipated to be recoverable, the pump should be designed for DNAPL recovery. These pumps have an inlet at the base of the pump so that accumulating DNAPL in the base of the screen or sump can be removed.

The following are the three main types of floating-product pumping systems:

- Floating Pump or Pump With Floating Inlet. These pumps automatically adjust to water-table fluctuations and pump down to a product layer of less than 0.05 feet.

- Preset Pump Elevation With Hydrophobic Filter. These pumps allow product (but not water) to flow into the pump mechanism. These pumps are often designed to pump down to a thin product film within a fairly short vertical range.

- Preset Pump Elevation With Electric Sensors or Density Controlled Valves That Only Allow the Pump to Pump Product. These pumps must be set at the elevation of the product layer to operate properly. In some cases, a conventional groundwater submersible pump can be used with electric sensors that turn the pump on or off if the product layer builds up to a fairly thick layer above and below the pump inlet.

There are also other types of floating-product pumping systems, including combinations of the above-mentioned system.

4.3.3 Total-Fluids Pumps.

Some sites with very low permeability often use a single total-fluids pump. A total-fluids pump pumps all fluids from the well, floating product, water, and/or DNAPL. The pumped liquid should be discharged to an above-ground product separator (See Subsection 4.4). Pneumatic pumps are often used in low-capacity applications because they can safely run dry without danger of burning out or damage from running dry.

When designing a total-fluids pumping system, designers should consider the pump's potential for freezing. See the discussion of pitless adapters in Subsection 4.4.

4.4 Other Devices.

In some cases, other devices are also part of the groundwater extraction system. A summary of these components includes the following:

Pitless Adaptor. Groundwater extraction systems should use a pitless adaptor or a pitless unit to transfer groundwater from the well to buried piping outside of the well casing to avoid freezing (See Driscoll, 1986; page 626). As a result, the water does not pass through any piping at or above the frost level. The pitless adaptor/unit allows the submersible pump to be removed from the well without significant plumbing difficulties.

The pitless adaptor/unit should be designed to allow access for taking water-level measurements. Some pitless adapters have very small holes that severely limit the diameter of the water-level indicator that can pass through the holes. In larger-diameter wells, pitless units are available that do not block access for product recovery pumps. Access into the well, past the pitless adaptor/unit, should be verified in the design.

A pitless adaptor/unit may be used for the groundwater pump in a two-pump system, but not for the product pump. Because depth adjustability for a product pump is important to the project success, the hoses for pumped product should extend out the top of the well. In addition, designers should use a support cable that allows simplified depth adjustability of the product pump. A pitless adaptor usually is not needed for the product pump since most floating products (or DNAPL) do not readily freeze.

> Note: The seals in pitless adapters and pitless units should be compatible with the contaminants.

Pitless adapters and pitless units may be used for total-fluids applications if a single pump is used for a water and product mixture.

Well Cover. Well covers are commercially available with padlock hasps, both with and without a connection to the electrical conduit for submersible pumps. The well cap should be lockable, however, when product recovery wells are installed, a small lockable enclosure may be installed over the well as a substitute for a locking well cap. This enclosure houses the electrical connections to the pump(s), winches for raising and lowering the pump(s), and any hoses to convey pumped product. If the wells are part of a high-capacity system, see NR 112 for additional Bureau of Water Supply requirements for well-cover designs.

Shroud. A shroud is a sleeve around the motor of a submersible pump that forces water past the motor to cool it. It is primarily used if the pump is installed very close to the base of the screen.

Manifold. The manifold consists of the piping system that is used to move the pumped liquids to the tanks and/or treatment system. It may be above ground, but in most cases it is buried. These manifold lines need to be constructed of a material that is compatible with the contaminants and are capable of holding the pressure and volume of the pumping system under worst case scenarios. If designers use a pneumatic-pumping system, the lines must be capable of holding the pressure of the regulated compressed air source. If designers use a submersible pump, the lines should be able to hold the pump pressure if the flow is blocked at the treatment location. Designers should use the working pressure rating, and not the burst pressure rating, when assessing the pressure capability for manifold lines. If heat tape is used, steel or other materials should be used instead of PVC. If a buried plastic pipe is used, a steel wire should be placed in the upper part of the trench before backfilling so that a metal detector can be used to locate the trench at a later time.

> Note: Burying a steel wire is unnecessary at sites where reinforced concrete pavement is used, since the metal detector will only "see" the rebar.

Flow Meter. A flow meter should be installed on the system to measure the amount of pumping from each well. It should be a totalizing-flow meter that indicates the total fluid pumped.

Product Storage Tank. A product tank is needed to contain the pumped product. See Attachment 2 for related rules.

Product Separator Systems. Product separator systems are tanks which allow separation of pumped product and water from total-fluids pumping systems. The tank may be baffled to limit mixing, and a coalescing separator may be used when the flow rates are too high for effective separation in a tank. See Attachment 2 for related rules.

Control Panel. The control panel should be designed specifically for each site. A panel with the appropriate sensors can provide the following:

- Automatic shut off, if the well is dewatered.
- High-/low-level sensors to turn a product pump on and off.
- Treatment system operation.
- Auto shut off for full-product tank.
- Auto shut off for overflow on separator tank.
- Other equipment control, such as blowers for vacuum-enhanced product recovery systems.
- Other data collection devices, such as an hour meter on pump operation, automatic telemetry for data transmission over the phone line, and possibly automatic data collection for water parameters (Ph, conductivity, etc.).

4.5 Groundwater Extraction System Design Report.

In some cases, the remediation system design is included in a comprehensive report with the results of the investigation. In other cases, the design is submitted separately. The design of the recovery well(s) must be submitted and approved prior to implementation, as required by Chapter NR 141. A report that includes the design of a groundwater extraction system should include the following information:

Discussion.

- Plume Capture. Designers should discuss the assumptions used to calculate the total groundwater extraction rate. Designers should also include a discussion of the geologic and hydrogeologic conditions and reasons why the plume-capture calculation method is appropriate.
- Design of the Wells. Extraction well details include the following:
  - bore-hole diameter,
  - screen length and diameter,

- slot size,
- casing depth, diameter and material
- filter pack and seal depths and specifications, and
- the drilling method.

Development method and planned disposition of development water should also be discussed.

- Manifold Design. The discussion should include the following:

  - pipe type,
  - materials of construction,
  - diameter(s),
  - location of valves, and
  - a description of instrumentation for measuring flow rate.

  Designers should discuss the depth of the manifold if it is buried.

- Pumping System Specifications. The discussion should include total anticipated gallons per minute and anticipated drawdown in each extraction well.

- Product Recovery. Designers should evaluate whether or not a product recovery system is necessary for the site.

- Operations and Maintenance Plan. The discussion should include a brief discussion of maintenance activities and frequency of site visits.

- Monitoring. The designer should propose a monitoring program for selected monitoring wells at the site that accurately measures the performance of the system. The DNR may require modifications to the proposed plan prior to implementation. See Subsection 5.4 for recommended progress report contents.

Figures.

- Designers should include a map of proposed well locations drawn to scale with the following information:

  - locations of proposed and existing groundwater extraction wells;
  - locations of monitoring well(s);
  - locations of the manifold and instrumentation;
  - location of the treatment system (if used) and the location of water discharge to sewer or surface waters;
  - location(s) of suspected and/or known contaminant source(s) (if differing contaminant types are present at a site, designers should identify the contaminant type at each source location);
  - free product zone (if present);

- groundwater contamination zone;
- groundwater extraction system capture zone under all anticipated shifts in the groundwater table under a given pumping rate;
- scale, north arrow, title block, site name, and key or legend;
- any other pertinent site information.

· Designers should include a current water-table map with the date of water-level measurements.

· A process-flow diagram indicating the piping layout with instrumentation and key components should also be included.

<u>Tables.</u>

· The report should include a table of water levels/elevations from all wells, over the life of the project.

· If floating product is present at the site, designers should include a table of product thicknesses over the life of project. This table can be combined with the water-level table.

<u>Appendices.</u>

· Plume-capture calculations for determining the well location(s) and the groundwater extraction rate should be included in the report. If plume capture-calculations are based on computerized modeling, the computer output should be included. The calculations determining hydraulic conductivity should be included, or a reference to the report that includes that data. Photocopies of hand written calculations and graphs are acceptable, IF THE CALCULATIONS ARE LEGIBLE. The initials and date of the person performing a quality assurance/quality control (QA/QC) check of all calculations should be included.

· Calculations estimating the drawdown in the extraction well(s) should be included.

· Designers should include calculations used to select the pumps; the type, size, manufacturer, and model of the pump; and the performance curve that is provided by the manufacturer of the pump.

· If a product recovery system is included in the system design, designers should include the type and specifications of the product pumps, the associated piping specifications, the specifications for the product tank, and disposition of recovered product.

· Designers should include calculations for determining the filter pack, well-screen slot-size, and entrance velocity. The grain-size analysis should also be included.

- A copy of the WPDES permit application, permit, request to a POTW, or approval letter from a POTW should be included.

5.0 Operation of a Groundwater Extraction System.

When a system is designed properly for the site, the system is likely to operate as expected. If the remediation system operator finds a method of operating the system more efficiently at any time, the system operator should evaluate those changes and submit them to the DNR for review prior to implementing the changes.

Generally, the operation of a groundwater extraction system includes periodic maintenance visits.

5.1 On-site Tests After Installation of the Extraction System.

After the groundwater extraction and treatment/disposal system is installed, designers should conduct a pumping test in a single extraction well as part of start-up operations to confirm the hydraulic conductivity estimate. This pumping test is not necessary if a 72 hour pumping test (24 hours for confined conditions) — at a flow rate that is at least 25 percent of the final remediation system pumping rate — was previously performed at the site.

A confirmation pumping test should be conducted for a minimum of 48 hours. This test does not need the frequency of water-level measurements that a predesign test requires because this test is used only to verify previous aquifer-testing results. In most cases, using popper tapes or water-level indicators are sufficient for this test, instead of using pressure transducers. Recommended frequency of water-level measurements for all wells at a generic site includes the following:

- Water-level measurements should be collected as rapidly as practical in all wells for the first two hours of operation. It is most important to frequently collect the measurements from the extraction well and nearby monitoring wells.
- Water-level measurements should be collected every hour for the next eight hours of operation.
- Water-level measurements should be collected at least twice a day for the next two to four days.

The system operator should leave the system in operation after the data is collected because the confirmation pumping test is not as important as the remediation system operation. Because the system continues to operate, recovery data cannot be collected. If multiple wells are installed, the start-up testing should only be conducted in a single well. After the start-up testing is completed, the operator should bring the additional wells on-line.

Because long-term data is available, using the Jacob straight-line method to calculate transmisivity of monitoring well data may be sufficient if the u value is less than 0.05. Using the new transmisivity value, the system operator should prepare a new plume-capture calculation to ensure the pumping rate is sufficient.

If a soil venting system is installed at the site, it should remain off during the start-up testing of the groundwater extraction system. This allows the aquifer to respond to the groundwater extraction system alone.

5.2 As-Builts Submittal.

Designers should submit as-built information in a report after the groundwater extraction system construction is complete. Because most of the information is in the design report, a separate submittal is usually not necessary, unless requested by the DNR. In most cases, the as-built information should be included in the first progress report after start-up. The as-built information includes the following:

- Results of on-site testing discussed in Subsection 5.1.
- Any deviations from the specifications in the design report.
- A map of actual-well locations drawn to scale. The map should include the following:
  - locations of existing groundwater extraction wells;
  - locations of monitoring wells;
  - the manifold and instrumentation locations;
  - suspected and/or known source location(s) (if differing contaminant types are present at a site, identify the contaminant types at each source location);
  - zone of soil contamination;
  - zone of groundwater contamination;
  - zone of free product (if present);
  - scale, north arrow, title block, site name, and key or legend; and
  - any other pertinent site information.
- Groundwater extraction well construction diagrams, boring logs, development information, and any other information required by Chapter NR 141.
- Any other pertinent information.

5.3 Groundwater Maps.

During regular site visits, water levels should be measured in all monitoring wells. Water-level maps should be prepared on a monthly basis for the first three months and quarterly thereafter. The maps should be used to assess the remediation system's ability to capture the plume. If the capture zone is insufficient, additional measures may be necessary, such as additional extraction wells and/or higher pumping rates.

If system operators use a soil venting system, vacuum-enhanced product recovery system, or air sparging system in conjunction with a groundwater extraction system, they should periodically shut off these systems long enough to allow the water table to respond to only groundwater extraction. After the water table has stabilized, operators should then collect water-level data and use it to calculate water elevations to produce the water-table map. However, if free product is present at a site and a vacuum-enhanced free-product recovery system is used, the operator should not shut off the vacuum if there is a possibility that additional product smearing may occur.

5.4 Reporting.

Reporting at the following frequency is recommended:

- Non-LUST Sites: The reporting frequency will be established on a site-specific basis.
- LUST Sites: Monthly for the first quarter; quarterly thereafter. The DNR Project Manager may request a different reporting schedule.

Progress reports to the DNR should be sequentially numbered starting with the first report after the remediation system start-up. Generally, the progress reports only need to be one or two pages of text in a letter format with supplementary tables and figures.

Reports to the LUST, ERP, or Superfund program should include the following:

Discussion.

- The discussion should include results and evaluation from analytical tests in monitoring wells. The evaluation should include a discussion of hydraulic containment and whether or not the plume capture is sufficient. Any appreciable changes in contaminant concentrations from previous rounds of sampling should also be evaluated.
- The total contaminant extracted to date in pounds or gallons of contaminant removed, based on contaminant concentration in the pumped water multiplied by the pumping rate should be included. In the case of product recovery, operators should report both the free product recovered and the dissolved phase extracted.
- System operational details, periods of shut down, equipment malfunctions, etc.
- The overall evaluation of the effectiveness of the system.
- Recommendations for future activities, if appropriate.
- The first progress report should discuss the results of the start-up testing discussed in Subsection 5.1.

Figures.

- A water-table map should be included in the figures. If multiple water-level readings were taken during the reporting period, include the water-table map from the most recent round of water levels. The site water-table map should verify that the plume capture is complete after the system has run for a minimum of one to four months (in most cases). If not, operators should describe plans to correct the situation in the text. The first progress report after pump start-up should also include a water-table map describing conditions immediately prior to pump start-up.

- A total contaminant removal graph, with time on the horizontal axis and cumulative contaminant removal in pounds or gallons on the vertical axis should be included in the figures. This graph should include the free-product recovery, the total dissolved-phase recovery, and the sum of the two.

Tables.

- A table of water levels/elevations and product levels or thicknesses from all wells at the site should be included.

- A table of groundwater chemistry data from monitoring and extraction wells should also be included.

Other Information.

- If analytical data is available from a laboratory, the lab reports should be included.

- A discussion of sampling procedures, analytical procedures, etc. is not required in each report, but operators should include a reference to the report that lists the procedures.

- Any other pertinent information or data should be included.

In all projects that include groundwater extraction, designers should report the groundwater discharge to the DNR Wastewater program or to the local POTW. Groundwater reporting requirements are not satisfied by reporting to the LUST, ERR, or Superfund program.

5.5 Project Close Out.

See Chapter 10 of the *Guidance for Conducting Environmental Response Actions* for project close-out procedures. Long-term monitoring or additional corrective actions may be necessary.

> Note: At the time this document was finalized, Chapter 10 has not been completed.

All wells should be abandoned in accordance with NR 141.25 upon final project closeout.

6.0 References.

Bear, J. 1979. *Hydraulics of Groundwater*. McGraw-Hill Inc., New York, N.Y.

Cooper, H.H, Bredehoeft, J.D., and Papadopulos, I.S. 1967. Response of a Finite Diameter Well to an Instantaneous Charge of Water. *Water Resources Research.* Volume 3, Number 1, pages 263 to 269.

Bouwer, H. and Rice, R.C. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells. *Water Resources Research.* Volume 12, pages 423 to 428.

Bouwer, H. 1989. The Bouwer and Rice Slug Test - An Update. *Ground Water*, Volume 27, Number 3, Pages 304 to 309.

Domenico, P.A. and Schwartz, F.W. 1990. *Physical and Chemical Hydrogeology*. John Wiley and Sons, Inc. New York, New York.

Driscoll, F.G. 1986. *Groundwater and Wells*, Second Edition. Johnson Division, St. Paul, Minnesota.

EPA, 1990, *Basics of Pump-and-Treat Ground-Water Remediation Technology*. EPA/600/8-90/003, March 1990.

Farr, A.M., Houghtalen, R.J., and D.B. 1990. Volume Estimation of Light Nonaqueous Phase Liquids in Porous Media. *Ground Water*, Volume 28, Number 1, Pages 48 to 56.

Fetter, C.W. 1988. *Applied Hydrogeology*, Second Edition. Merrill Publishing Company, Columbus, Ohio.

Fetter, C.W. 1993. *Contaminant Hydrogeology*. Macmillan Publishing Company, New York, New York.

Freeze, R.A. and Cherry, J.A. 1979. *Groundwater*. Prentice Hall Inc., Englewood Cliffs, NJ.

Grubb, S. 1993. Analytical Model for Estimation of Steady-State Capture Zones of Pumping Wells in Confined and Unconfined Aquifers. *Ground Water*, Volume 31, Number 1, Pages 27 to 32.

Hughes, J.P., Sullivan, C.R., and Zinner, R.E. 1988. Two Techniques for Determining the True Hydrocarbon Thickness in an Unconfined Sandy Aquifer. *Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Restoration*, November 1988, Pages 291 to 314.

Javandel, I. and Tsang, C. 1986. Capture Zone Type Curves: A Tool for Aquifer Cleanup. *Ground Water*, Volume 24, Number 5, Pages 616 to 625.

Karasaki, K., Long, J.C.S., and Witherspoon, P.A. 1988. Analytical Models of Slug Tests. *Water Resources Research*, Volume 24, Number 1, pages 115 to 126.

Kemblowski, M.W. and Chiang, C.Y. 1990. Hydrocarbon Thickness Fluctuations in Monitoring Wells. *Ground Water*, Volume 28, Number 2, Pages 244-252.

Kruseman, G.P. and de Ridder, N.A., 1990. *Analysis and Evaluation of Pumping Test Data*, Second Edition. International Institute for Land Reclamation and improvement, Wageningen, The Netherlands.

Masch, F.D. and K.J. Denny. 1966. Grain Size Distribution and its effect on the permeability of unconsolidated sand. *Water Resources Research*, Volume 2, Number 4, pages 665 to 677.

Neuman, S.P., 1974. Effect of Partial Penetration on Flow in Unconfined Aquifers Considering Delayed Gravity Response. *Water Resources Research*, Volume 10, Number 2. Pages 303 to 312.

Neuman, S.P., 1975. Analysis of Pumping Test Data From Anisotropic Unconfined Aquifers Considering Delayed Gravity Response. *Water Resources Research*, Volume 11, Number 2. Pages 329 to 342.

Robbins, G.A., Bristol, R.D., and Roe, V.D. 1989. A field Screening Method for Gasoline Contamination Using a Polyethylene Bag Sampling System. *Ground Water Monitoring Review*, Fall, 1989. Pages 87 to 97.

Shepherd, R.G. 1989. Correlations of Permeability and Grain Size. *Ground Water*, Volume 27, Number 5, Pages 633 to 638.

Strack, O.D.L., 1989. *Groundwater Mechanics*. Prentice Hall, Inc., Englewood Cliffs, NJ.

Testa, S.M. and Paczkowski, M.T. 1989. Volume Determination and Recoverability of Free Hydrocarbon. *Ground Water Monitoring Review*, Winter 1989, Pages 120 to 128.

Todd, D.K. 1980. *Groundwater Hydrology*, Second Edition. John Wiley & Sons, Inc. New York, NY.

Department of Natural Resources. 1993. *Guidance for Treatment Systems for Ground Water and Other Aqueous Waste Streams*. PUBL-SW184-93.

Department of Natural Resources. 1993. *Guidance for Design, Installation and Operation of Soil Venting Systems*. PUBL-SW185-93.

Wisconsin Administrative Code NR 112, Private and Non-Community Well Construction and Pump Installation Code.

Wisconsin Administrative Code NR 141, Groundwater Monitoring Well Requirements.

Attachment 1
Waste Classification of Petroleum Products

State of Wisconsin

CORRESPONDENCE/MEMORANDUM

DATE: January 3, 1992 FILE REF: 4430
TO: District Solid & Hazardous Waste Program Supervisors
FROM: Paul P. Didier- SW/3
SUBJECT: Waste Classification of Petroleum Products

Recently there have been several questions raised concerning the regulation as hazardous waste of off-specification petroleum products. Please note that products which meet the petroleum product specifications of ch. ILHR 48, Wis. Adm. Code are not covered by this memo. "Petroleum product", in this instance, means a product regulated by DILHR under ch. ILHR 48, the Petroleum Products Administrative Code. It does not include waste oil, waste gasoline, or sludges generated during underground tank closures, or media contaminated by petroleum products. Products may be off-specification due to water content, ethyl alcohol content or a number of other reasons. The closure of a petroleum product storage tank system may also result in the necessity to manage petroleum products which do. not meet DILHR requirements for sale to consumers. In many cases these materials can be (and currently are) reintroduced into the petroleum product market place. The purpose of this memo is to clarify our position on the management of off-specification materials. Owners and responsible parties should be encouraged to recover free product in tank closure situations. They should be required to conduct this work in accordance with applicable rules and guidance.

If an off-specification petroleum product falls outside the scope of (no longer meets the specification for its intended use) or cannot be further managed (downgraded or blended to meet ILHR requirements) under ch. ILHR 48, Wis. Adm. Code, then it is considered to be a solid waste and falls within the jurisdiction of the Department of Natural Resources. The generator must determine if the waste is hazardous and manage it accordingly. Options other than disposal, such as the secondary fuel program, do exist for petroleum waste that is hazardous waste.

Petroleum products that either meet the standards of ch. ILHR 48, Wis. Adm. Code or those products that will be blended to meet the standards fall within the jurisdiction of the Petroleum Inspection Program of DILHR. Wastewater; gasoline/water interfaces; petroleum directly above the product/water interface (within 2 inches per DILHR guidance); and sludges fall within the scope of the Wisconsin Department of Natural Resources regulations as wastes.

The following requirements have been established by the DILHR Petroleum Inspection Program for the handling and use of petroleum products under its jurisdiction which are generated during tank system closures. They also apply to the management of off-specification petroleum products. These requirements reflect DILHR's authority under ch. 168, Wis. Stats. and ch. ILHR 48, Wis. Ada. Code.

.1. The removal and transfer of any off-specification product destined for use or return to a terminal or refinery must be by a tank vehicle which complies with the "Standards for Tank Vehicles for Flammable and Combustible Liquids; NFPA-385."

2. Off-specification product may be:

   a. Returned to a terminal slop tank, if a terminal will accept it.

   b. Returned to a refinery, if the company will accept it.

3. Petroleum product removed from a tank system may be managed in the following ways:

   a. Gasoline may be transferred to another facility for storage and use. Storage must meet the standards established in the Flammable and Combustible Liquids Code. In this case the material must meet specifications of ch. ILHR 48, Wis. Adm. Code. Gasoline may also be transferred to another facility for blending. The blended product must meet ch. ILHR 48, Wis. Adm. Code, specifications.

   b. Terminals or refineries may purchase off-specification gasolines and blend them with new gasoline at their facilities at a rate not to exceed ½ of 1%.

   c. Off-specification oils must be down-graded to #2 fuel oil. Products classified as kerosene, #1 diesel, #1 fuel oil or #2 fuel oil may be blended with new #2 fuel oil (at up to a 50% rate) and used or sold for heating purposes.

   d. Off-specification products heavier than #2 fuel oil may be blended with an equal or heavier stock, at up to a 50% rate, and sold or used for heating purposes.

   e. Off-specification oils may also be sold without blending for nonsensitive burner and heating use if the purchaser has established itself as a qualified buyer/user with the DILHR District Petroleum Inspection Office.

4. When off specification product quantities of 500 gallons or more are removed from a tank system, the DILHR District Petroleum Inspection Office must be contacted. Based upon the contact, the Petroleum Inspection staff will determine the disposition of the product. The staff may:

   a. Sample and test the product to determine compliance with ch. ILHR 48, Wis. Adm. Code, and then provide directions for disposition.

   b. Allow transfer of the product to another station or facility for use or sale.

   c. Classify the product as falling outside the scope of ch. ILHR 48, Wis. Ada. Code (material is waste).

At locations where the gas is floating on the water table in sufficient amounts for it to be recovered by itself, it may be handled in accordance with items 1 through 4 without obtaining a hazardous waste I.D. number. However, once items 1 through 4 are no longer available options, then it is a waste material and must be managed in accordance with item 5 (below) and chs. NR 600 to 685 Wis. Adm. Code.

5. Petroleum wastes (material that can't be blended or downgraded) pumped directly from the ground into a tank without any treatment or separation are solid waste and must be managed as hazardous waste if they exhibit the characteristic of ignitability (in the future, these may be TCLP hazardous wastes). This material cannot be sold for use by consumers under any circumstances.

This issue was previously addressed prior to this in a joint memo from Barb Zellmer and Mark Giesfeldt to you dated December 7, 1990. For ease of reference the two pertinent items from that memo are repeated below. You may wish to review your copy of that memo for other related information.

"8. Is petroleum product which is recovered from the water table a waste?

Petroleum product recovered from the water table is a waste only if it cannot be used as a product. The factsheet titled "Managing Petroleum Products" provides guidance on blending "old" petroleum from tanks with new product, and returning petroleum to terminal "slop tanks."

NOTE: There may be taxation issues which apply to recovered product. This should be checked with the Department of Revenue.

9. What if a recovery system recovers both free product and groundwater?

Systems which recover both free product and groundwater may require an EPA identification number for on-site separation tanks because product separated in the tank may be a hazardous waste if it is unsuitable for fuel purposes. Refer to the "Managing Petroleum Products" factsheet regarding allowable petroleum uses. Recovered groundwater may be directly discharged to a sanitary sewer following approval from a publicly owned treatment plant. If groundwater is recovered at a site which does not fall under the TCLP deferral and it is transported by tanker to a was tewater treatment system TCLP analysis is required and a hazardous waste transportation license may be needed.

Discharge of groundwater to surface water requires a WPDES permit. If the contaminated water is treated to meet WPDES permit limits TCLP requirements would not apply. Refer to the July 9, 1990 memo from Ken Wiesner for additional wastewater guidance."

A copy of the factsheet "Managing Petroleum Products" is attached.

Facilities which have a gasoline water separation system following the tank in which the contaminated groundwater/gasoline mixture is pumped, need to obtain an EPA I.D. number and report the activity. The recovered petroleum material may be handled in a manner consistent with items 1 through 4 previously addressed. This could be viewed as legitimate recycling under the hazardous waste program. The operation would be covered by ch. NR 625, Wis. Adm. Code Hazardous Waste Recycling.

U.S. EPA does not regulate off-specification petroleum products that are not ..considered to be waste. When an off-specification petroleum product is a hazardous waste and is burned for energy recovery it is regulated in accordance with the recycling provisions of 40 CFR Part 266-Standards for the management of specific hazardous wastes and specific types of hazardous waste management facilities-subpart D. Both state and federal rules require both generators and transporters of hazardous waste fuel (secondary fuel) to comply with applicable hazardous waste management standards.

In conclusion, off-specification petroleum product that cannot be blended or downgraded is considered a solid waste. The generator must determine if the waste is hazardous and manage it accordingly. Options such as the hazardous waste fuel (secondary fuel) program do exist for petroleum waste that is hazardous. For example, WR&R, Avganic, and Milwaukee Solvents all have secondary fuel programs.

At this time, DILHR is also working on its own formal rule interpretation on the management of off-specification petroleum products. When it is finalized, we will forward a copy of it to you.
if you have questions do not hesitate to contact Ed Lynch at (608) 266-3084 or

Laurie Egre at (608) 267-7560.

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Attachment 2
DILHR’s Design Criteria for Process Equipment Buildings Associated with Environmental Remediation of UST/AST Sites

SAFETY & BUILDINGS DIVISION
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State of Wisconsin
Department of Industry, Labor and Human Relations

Program Letter 10- UST/AST Program

ILHR 10 POSITION STATEMENT

Design Criteria for Process Equipment Buildings Associated With Environmental Remediation of UST/AST Sites

Issue
Soil and groundwater contamination remediation practices include several processes which involve the potential hazards from flammable/combustible liquids and associated vapors. The equipment associated with these processes often is protected from the weather elements by enclosure within a building, which serves to trap vapors posing a greater hazard. Presently this type of facility escapes direct code application due to the unique nature and limited application. The building code does not clearly identify this type of structure and it's respective use within the scope of the individual chapters. Proper design criteria is subject to individual interpretation and discretion. The state has experienced approximately six fires or explosions within buildings of this type within the past two years. Representatives of firms designing and constructing remediation facilities have requested guidance in applicable rules and fire prevention measures.

A work group was created to address the use and hazards associated with buildings enclosing remediation equipment and associated process. The work group determined that *pump and treat, vacuum pumping,* and *free product removal* processes pose a significant fire/explosion risk due to the existence of flammable or combustible liquids and/or flammable fumes or vapors. It was also determined that these facilities have very similar hazard characteristics, therefore making a single design standard applicable to all three processes.

The work group evaluated the physical characteristics of the equipment and the operating and maintenance practices associated with the respective processes. The design recommendations are based upon the requirements within Wisconsin Administrative Codes and National Standards: ILHR 50-64, ILHR 10, NFPA 30, and NEC NFPA 70. The building and its operation meet the definition of *process* in NFPA 30(1990 Edition) Chapter 5 Operations. The facility design standard in Chapter 5-3 is used to establish the basic criteria for the remediation building. Due to the limited size of the building, the respective remediation activities, and the reduced degree of risk, some of the requirements of NFPA 30 Chapter 5 are not practical.

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Design Criteria

Setback	(A) NFPA 30 5-3.1.1 and Table 5-3.1.1 address the *process vessel,* in this application the flammable/combustible liquid collection tank. Tanks ‘275 gallon capacity must be located 5’ from property line and 5’ from any public way or important building; a tank 276 to 750 gal. 10, from property line and 5’ from a public way and important building. (B) NFPA 30- 5-3.1.3 requires that *liquid processing equipment,* such as pumps, heaters, filters, exchangers, etc., shall not be located closer than 25’ to property lines that can be built upon or to the nearest important building. The philosophy is that such equipment is more prone to leakage than the process tank. This spacing requirement may be waived where the exposures are protected by a blank wall having a fire resistive rating of not less than 4 hours. Since remediation buildings contain the process vessel and the liquid processing equipment. the most restrictive setback of 25’ (B above) shall apply.
Building construction	NFPA 30-5-3.2.1: Processing buildings or structures shall be of fire resistive or non combustible construction.
Electrical	Electrical area classification NEC article 514 and NFPA 30 Table 5-3.5.3. Electrical emergency shut-down in exterior locked cabinet or in adjacent building if 24 hour access.
Venting of building	NFPA 30-5-3.3. Natural gravity or mechanical ventilation capable of maintaining a minimum of I CFM/Vt^2. 18 AFF. Areas that may pose temperatures above the flash point of the liquid shall be ventilated at a rate sufficient to maintain the concentration of vapors within the area at or below 25% of the lower flammable limit.
Tank construction	UL or similar listing for product contained within.
Tank located inside of building	Vessels larger than 60 gallons. NFPA 30-4-4.1.2 4 curb. Breach in floor for plumbing must be protected by 4” lip or be sealed against liquids. Tank must be vented to the outside of the building.
Tanks located outside of building.	Secondary containment. Collision protection if in traffic area.
Product & vapor piping	All piping and joint compounds shall be compatible with the product. Vent piping shall be of steel or approved metal construction only.

Drum storage inside of buildings	Inside storage of drums containing Class I or II liquid product resulting from the remediation process is not recommended, but is not prohibited if the walls and ceiling are of a 1 hour fire resistive rating. Drums that are being filled must have adequate venting to prevent excessive pressure from rupturing the container.
Drum storage outside of Building	Drums shall be stored in compliance with NEPA 30-4-8 of Outdoor Storage.
Signage	NFPA 704 placard. WARNING- No Smoking. 24 hour notification number.
Notification	Notice to local fire department of installation, including name, address and telephone number(s) for 24 hour notification. Identify access to building, and shut-down process. Twenty-four hour access or locked exterior panel.
Retroactivity	Non complying electrical, non complying interior and/or tank ventilation, fire department notification, and signage.

Plan review

ILHR 10 requires that the installation of *tanks for the* storage of *flammable or combustible liquids* be submitted for plan review and approval to the authorized program operator for the geographic fire jurisdiction of the site. The installation of the product storage tank and the associated product piping and vent piping shall be conducted by an ILHR 10 Certified Installer.

Remediation buildings are designed to be temporary structures with an expected use life of I to 5 years. *Local operators reviewing plans are directed to contact the area DILHR Tank Inspector when plans or on-site inspections reflect that the building may be over built for the intended remediation use.* Characteristics that reflect a structure with a questionable design may be: footings, overhead garage door, floor area, windows, construction material, surface improvements, etc. DILHR should also be notified if the facility appears to have components in place or design characteristics for the addition of utilities (eg. sewer or water) at a later date.

Common remediation buildings are a windowless single story structure, on a floating cement slab, less than 200 sq. ft. floor area, with a single walk-through door.

William J. Morrissey, Director
Bureau of Petroleum Inspection
and Fire Protection

Sheldon Schall, Chief
Fire Protection and Storage Tank
Section

May 25, 1993

Attachment 3

Two-dimensional Plume-Capture Calculations With UniformHorizontal Flow Under Static Conditions

Attachment 3

Two-dimensional Plume-Capture Calculations With Uniform Horizontal Flow Under Static Conditions

This method is usually used for sites with relatively high-hydraulic conductivity and high natural groundwater migration rate. Refer to the references for a further discussion of assumptions and applicability.

Key assumptions include the following:

- Steady state, no transient affects.
- Location of a single, fully penetrating extraction well at the coordinate origin in a confined aquifer.

  Note: Although the method is for confined aquifers, since the drawdown is less than 20 percent of the total-aquifer thickness (in most cases), the method usually provides reasonable results in unconfined aquifers. If the drawdown exceeds 20 percent, the method in Grubb (1993) or another method should be used.
- Uniform horizontal flow (when no pumping occurs) from the plus x direction towards the minus x direction; no water enters the aquifer at the base.
- No dispersion; assume that all contaminants travel on the streamlines.
- The aquifer is isotropic.

Equation 4.32 from Todd, (page 122) is:

$$Y_L = \pm \frac{Q}{2\ K\ b\ i}$$

The method uses consistent units.
Q is the pumping rate,
K is the hydraulic conductivity,
b is the aquifer thickness,
i is the slope of the water table.

Solving for Y_L provides one-half of the capture zone width at an infinite upgradient distance.

The following equation 4.31 from Todd, page 121, provides the capture zone:

$$-\frac{y}{x} = \tan\left(\frac{2\ \pi\ K\ b\ i}{Q}\ y\right)$$

Solving for x, given different values for y (that are less than Y_L), the x and y coordinates of specific points along the capture zone can be calculated. Note: The tangent function uses radians instead of degrees.

To determine the stagnation point use equation 4.33 from Todd on page 123:

$$X_L = -\frac{Q}{2\pi K b i}$$

An example and sample set of results are as follows:

Assume the following:

Q = 3850.3 cubic feet per day (corresponds to 20 gpm)
K = 35 feet per day (corresponds to 1.23 E-2 cm/sec)
b = 50 feet
i = 0.01

Solve for Y_L,

$$Y_L = \pm\frac{Q}{2 K b i} = \pm\frac{3850.3}{2 * 35 * 50 * 0.01} = 110.01 \text{ feet}$$

Using differing positive values of y (less than Y_L), calculate x. For instance at $y = 100$, x is:

$$-\frac{y}{x} = \tan\left(\frac{2\pi K b i}{Q} y\right)$$

$$-\frac{100}{x} = \tan\left(\frac{2 * \pi * 35 * 50 * 0.01}{3850.03} * 100\right),$$

$$x = -100 / \tan\left(\frac{2 * \pi * 35 * 50 * 0.01}{3850.03} * 100\right) = 340.3$$

y (feet)	x (feet)
100	340.3
80	69.3
60	8.6
40	-18.3
20	-31.1

Because the capture zone is symmetrical, each data point can also be plotted at the negative of the y value.

y (feet)	x (feet)
-100	340.3
-80	69.3
-60	8.6
-40	-18.3
-20	-31.1

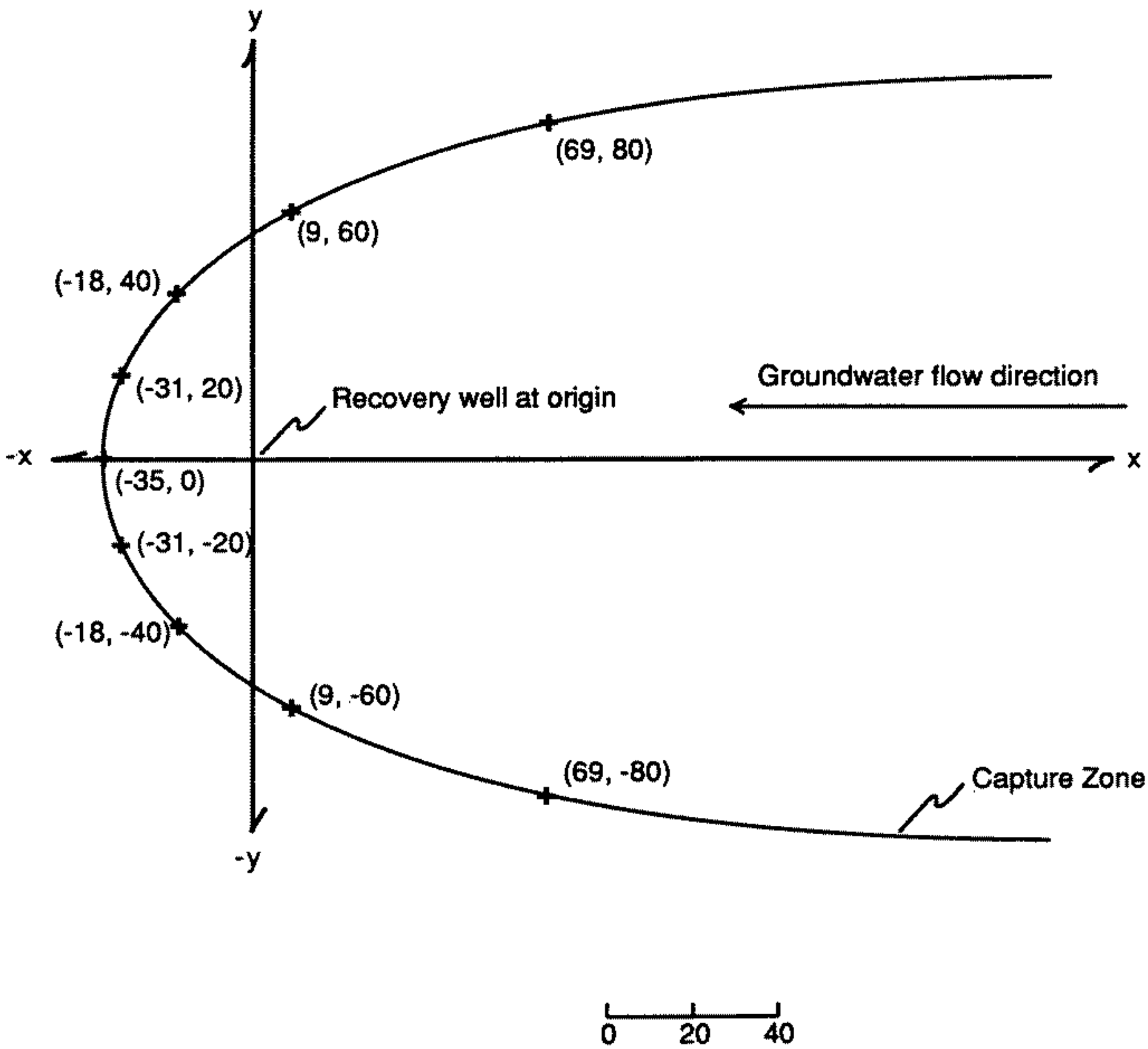
Solve for X_L at the stagnation point. Note: The point at $y = 0$ is the stagnation point downgradient of the extraction well,

$$X_L = -\frac{Q}{2\pi K b i} = -\frac{3850.03}{2 * \pi * 35 * 50 * 0.01} = -35.0$$

A map is then created by plotting the above points and fitting a curve to the points. The resulting curve is the capture zone. See Figure A3-1. The capture zone is then overlaid on a site map, the origin (x=0,y=0) is the extraction well, and the downgradient direction of groundwater flow is aligned with the minus x axis.

See Subsection 4.1 for the applicable requirements to ensure a large enough capture zone to account for the effects of dispersion.

Figure A3-1
Plume capture



Example based on
20 GMP pumping rate
35 feet/day hydraulic conductivity
50 foot aquifer thickness
0-01 water table slope

Attachment 4

Two-Dimensional Plume-Capture Calculations With a Horizontal Water Table Under Static Conditions

This method is usually used at sites with relatively low hydraulic conductivity and minimal natural groundwater migration. Refer to the references for a further discussion of assumptions and applicability.

Key assumptions include the following:

- The water table is flat with no slope.
- A single, fully penetrating extraction well is located at the center of the contamination.
- The aquifer is isotropic and unconfined.
- Steady state; no transient affects.

Equation 4.18 from Todd (1980, page 118),

$$Q = -2 \pi r K h \frac{dh}{dr}$$

The method uses consistent units.
Q is the pumping rate,
K is the hydraulic conductivity,
h is the aquifer thickness under static conditions,
dh/dr is the slope at a radial distance *r*.

Solve for *Q*, disregard the minus sign.

For a numerical example, assumptions include;

- distance to farthest point of contamination (*r*) is 50 feet;
- thickness of aquifer (*h*) is constant throughout at 35 feet prior to pumping;
- hydraulic conductivity (*K*) is 3.5 feet per day (corresponds to 1.23 E-3 cm/sec);
- an inward slope of 0.015 (*dh/dr*) is desired at the perimeter. Note: This is 50% greater than the minimum recommended in subsection 4.1;
- no water enters the aquifer at the base and there is no infiltration; and
- drawdown at *r* is insignificant and is assumed to be zero.

$$Q = -2 \pi r K h \frac{dh}{dr} = -2 * \pi * 50 * 3.5 * 35 * 0.015 = 580 \frac{ft^3}{day}$$

which corresponds to 3 gpm

After the flow rate is determined, the drawdown (*s*) in the well is predicted to see if it is reasonable. Formula 3.7 on page 65 in Kruseman and de Ridder (1990) can predict drawdown assuming a long period of time (such as a year). Note: Similar formulas are also given in Fetter (1988, page 170), Driscoll (1986, page 219) and Freeze and Cherry (1979, page 347).

Use consistent units.

$$s = \frac{2.3\ Q}{4\ \pi\ T}\ Log_{10}\ \frac{2.25\ T\ t}{r^2\ S}$$

Where $T = K\ h = 3.5 * 35 = 122.5\ \frac{ft^2}{day}$

Additional assumptions for the numerical example include;

- well radius (*r*) is 0.25 feet;
- storage or specific yield (*S*) is 0.2;
- time (*t*) is one year (or 365 days); and
- the well is adequately developed to be efficient.

$$s = \frac{2.3\ Q}{4\ \pi\ T}\ Log_{10}\ \frac{2.25\ T\ t}{r^2\ S}$$

$$= \frac{2.3 * 580}{4 * \pi * 122.5}\ Log_{10}\ \frac{2.25 * 122 * 365}{0.25^2 * 0.2} = 6.0\ feet$$

Designers can then make a partial penetration correction, if necessary. There is no ideal mathematical solution for an unconfined situation where the screen is at the top of an aquifer. Designers should use a confined solution, even though it is not mathematically correct, it is better than no correction. An additional assumption for the example includes;

- The plume is in the uppermost 20 feet of the aquifer, therefore, the designer should select a 20 foot partially penetrating well screen that intersects the water table at the top of the screen.

In this example, Figure 9.35 in Driscoll (1986, page 250) is used to estimate the drawdown in a partially penetrating well. When calculating the percentage of aquifer screened or the thickness of the aquifer (*b*), use the thickness of the aquifer and screen length under pumping (not static) conditions. Since the aquifer is partially dewatered and the top of the screen is set at the top of the static aquifer, both the aquifer thickness and the effective screen length are shortened by the drawdown.

Therefore;

(h-s) is substituted for *b*,

$$\frac{h-s}{r} = \frac{35 - 6.0}{0.25} = 116$$

Therefore Curve E is used on Figure 9.35.

$$\text{Percentage of aquifer screened} = \frac{20.0 - 6.0}{35.0 - 6.0} = 0.48 = 48 \text{ percent}$$

From Figure 9.35, the percent of maximum specific capacity attainable is 70 percent.

Therefore the drawdown (*s*) is increased to,

$$s_p = \frac{s}{0.7} = \frac{6.0}{0.7} = 8.5$$

Where the term s_p represents the drawdown in a partially penetrating well.

It is generally good to have a minimum of 5 feet of screen in the aquifer under pumping conditions. In the above numerical example, the predicted drawdown is roughly 8.5 feet in a 20 foot screen, which means that there will be roughly 11.5 feet of water in the screen. Subsection 4.2 recommends a maximum drawdown of 10 feet in water-table wells with no free product. That is only a recommendation; economic considerations may require fewer wells with greater drawdown in some situations. Remediation system designers should use their professional judgement.

The method for partial penetration in Driscoll (1986) assumes confined conditions, therefore, some error is likely when the method is applied to unconfined situations, such as the above example. Another solution, using different mathematical principles and assumptions, is included in Todd (1980).

Note: If the Kozeny Equation on page 250 in Driscoll is used, there is a typographical error in early copies of the book. The term "... plus the seventh root of ..." is wrong, it should be "... plus seven times the square root of ..."

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