

# GUIDANCE FOR DETERMINING WATER SUPPLY WELL VULNERABILITY AT TIER 3

01/07/04

## Introduction

Procedures for responding to a release from petroleum underground storage tank (UST) systems are set out in Chapter 135 of the Iowa Administrative Code (IAC), Title 567. Site investigation after a release of petroleum from a UST system follow a three-tiered risk-based strategy known as Risk-Based Corrective Action (RBCA). This guidance document addresses particular situations involving petroleum contamination risk to water supply wells which a groundwater professional believes are not accurately characterized for risk using Tier 1 or Tier 2 approaches.

“Tier 3 site assessment” is defined in Chapter 135 as “a site-specific risk assessment utilizing more sophisticated data or analytical techniques than a Tier 2 site assessment.” A later section of the chapter goes on to say:

“Where site conditions may not be adequately addressed by Tier 2 procedures, a Tier 3 assessment may provide more accurate risk assessment. The purpose of Tier 3 is to identify reasonable exposure levels of chemicals of concern and to assess the risk of exposure to existing and potential receptors based on additional site assessment information, probabilistic evaluations, or sophisticated chemical fate and transport models in accordance with 135.11(455B).” [567 IAC 135.8(c)] (underscore added.)

The underlining in the rule quoted above emphasizes a Tier 3 assessment does not need to be complicated, extensive, or unduly sophisticated. A subsequent section elaborates:

“A Tier 3 assessment may include but is not limited to the use of more site-specific or multidimensional models and assessment data, methods for calibrating Tier 2 models to make them more predictive of actual site conditions, and more extensive assessment of receptor construction and vulnerability to contaminant impacts...” [567 IAC 135.11(2)] (underscore added.)

The underlined phrase in the quote above is the basis for this document. The document provides guidance to the groundwater professional in dealing with high risk sites involving drinking water well or non-drinking water well receptors. The guidance consists of two sections and is intended to assist the groundwater professional with: 1) identifying areas in which to focus assessment efforts; and 2) producing Tier 3 work plans and reports of necessary completeness and consistent quality.

The goals of corrective action are to prevent adverse health effects through human exposure to chemicals of concern and to prevent environmental impact from a petroleum release. This is typically accomplished by cleaning up the chemicals of concern to Target Levels or by severing the pathway between a chemical source (e.g., leaking UST site contamination) and a receptor (e.g., drinking water well). The Tier 3 assessment is targeted at collecting site-specific information that permits an alternative characterization of risk to a receptor than was identified using the Tier 2 fate and transport model. The desired result is to establish with some high degree of certainty the receptor will not be at risk from the petroleum release, and normal activity involving the receptor can proceed.

A water supply well can be in a high risk situation if it is located within the Tier 2 simulated contaminant plume area or located within the actual contaminant plume area. In either case, a Tier 3 assessment might show the high risk condition found using the Tier 2 fate and transport model does not, in fact, exist, and further corrective action is either reduced in scope or unnecessary. A Tier 3 assessment is undertaken first to document a situation a groundwater professional feels has been inaccurately designated as high risk due to the limitations of the Tier 1 and Tier 2 assessments, and secondly, to portray the risk accurately.

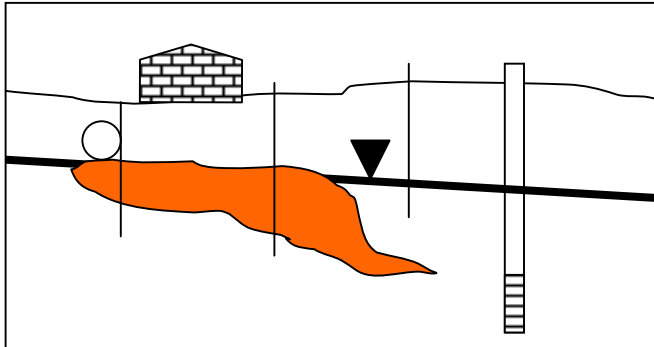
## SECTION 1.

### **Example Situations**

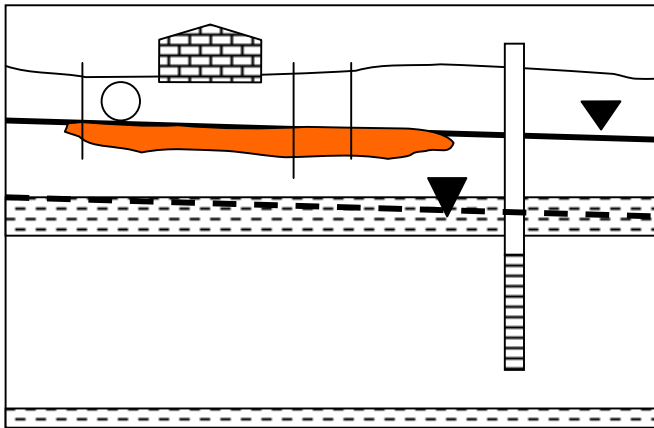
Tier 2 site assessment and modeling generate mapped plumes of groundwater contamination for chemicals of concern. Actual plumes (based on sample data) and simulated plumes (modeled with Tier 2 software using limited site data and fixed input parameters) are produced showing the areal relationships among contaminant source, known plume dimensions, groundwater flow direction, and identified receptors. For sites having simple hydrostratigraphy dominated by natural advection, the Tier 2 plumes can represent the situation with reasonable accuracy (assuming site-specific parameters such as hydraulic conductivity (K) and gradient (i) are accurate). But for sites where a pumping well dominates the local groundwater flow, or the hydrostratigraphy is more complex, the Tier 2 representations can be greatly inaccurate.

Three situations involving water wells are portrayed in the following illustrations. Situations I and II are commonly encountered throughout Iowa in communities situated along rivers. Situation II might be more prevalent than Situation I in the major river valleys, and *vice versa* in medium-sized and small river valleys (the qualitative valley size designation relates directly to the extent of flood plain deposits). Situation III is commonly encountered in eastern and northern parts of Iowa where carbonate bedrock occurs near the land surface. It is not the intent of this guidance to imply any situation found in Iowa will fit one of these three examples. Rather, the intent is to illustrate how certain situations can be approached at Tier 3. The groundwater professional must employ his or her own skill and judgement in characterizing a site situation and in designing a Tier 3 Work Plan.

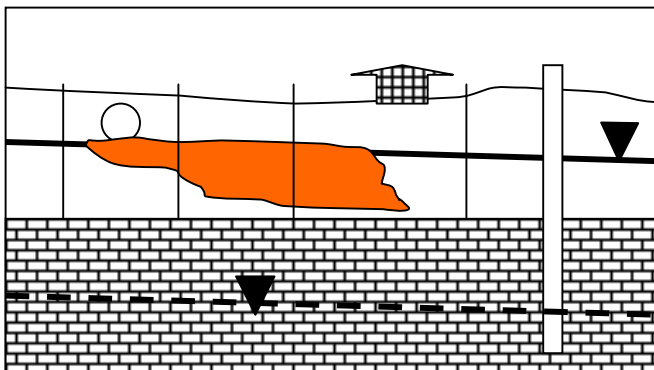
Situation I. Water Supply Well screened in same unconfined aquifer as contamination source.



Situation II. Water Supply Well screened in confined aquifer but separated from contamination source in unconfined aquifer.



Situation III. Water Supply Well with open hole completion in bedrock but below contamination source in glacial drift.



In situation I, contamination is in the same hydrostratigraphic unit as the well screen. If the well is pumped at a high rate, a risk exists that some water flowing through the contaminated zone will reach the screened interval. A Tier 3 assessment of such a

situation must show that the contaminant plume cannot enter the well or reach the well screen. Important factors to consider are plume age and stability, structural integrity of the well, well pumping rate and induced gradients, and potential effects of increased well pumping.

In situation II, the well produces from a confined or semi-confined aquifer, and the contaminated zone is in an overlying unconfined aquifer. The well screen is separated from the contaminated zone by an aquitard. Contamination might get into the well through faulty casing or grouting, or through the aquitard if the well is pumped at a high rate and the aquitard is leaky. A Tier 3 assessment of such a situation must show that the contamination plume cannot enter the well nor reach the well screen. Important factors to consider are plume age and stability, structural integrity of the well through the unconfined aquifer and whether water produced from the confined aquifer is sourced in the unconfined aquifer.

In situation III, the well is an open hole completion in an unconfined bedrock aquifer. The contaminated zone is in overlying glacial till. A Tier 3 assessment of such a situation must show the contamination plume cannot enter the well. Important factors to consider are plume age and stability, structural integrity of the well through the glacial till, the likelihood fractures, karst features, and bedding planes in the aquifer provide ready hydraulic connection between the bedrock surface and the well bore, and whether water from the glacial till has the potential to infiltrate the bedrock aquifer.

### **Required Information**

Any Tier 3 assessment report involving a water supply well must include details of the well construction, pumping rate, pumping schedule, and relevant aspects of hydrogeology in the site vicinity. Diligence by the groundwater professional in determining this information is expected. Requirements and suggestions for presenting this information are given in Section 2, below.

### Needed information and sources

Well information important in producing a compelling argument in a Tier 3 Report about a water supply well is listed below. The depth of the screened interval, the static water level (SWL), pumping rate and pumping schedule are of overriding importance. Other items of information become increasingly important if casing integrity is an issue, and if a pumping test or numerical modeling is proposed.

Well Use (e.g., drinking water (public/private) irrigation, livestock, industrial.)

Well total depth.

Depths of screen(s) top(s) and bottom(s).

Screen diameter(s).

Depth of casing bottom (if open hole completion).

Casing diameters and depth intervals.

Well seal or grouting schedule.

Filter pack top, bottom, and thickness.

Filter pack texture and composition (e.g., 5 mm gravel).

Static water level.

Pumping water level.

- Pump depth.
- Pumping schedule.
- Pumping rate (gpm actually produced).
- Date drilled.
- Maintenance records.
- Water analyses. See text for analysis suggestions.

If a diligent search turns up insufficient information about the well, the groundwater professional must examine and measure the well firsthand to the extent possible. It is normally possible to determine the aquifer from which the well produces by knowing the well depth and comparing the records of nearby wells. In such cases of indirect aquifer determination, the groundwater professional must report an extensive survey of surrounding wells and other information sources so uncertainty as to the identity and stratigraphic position of the producing aquifer is minimized. Information about water well construction might be obtained from the following sources:

- Iowa Geological Survey- GeoSam website: [www.igsb.uiowa.edu](http://www.igsb.uiowa.edu).
- DNR Water Quality Bureau or field office.
- Well owner.
- Well driller.
- County sanitarian.
- Local health department.

Hydrostratigraphic information important for demonstrating pathway completeness or incompleteness between contamination and the water supply well is listed below. Aquifer type, hydrologic parameters, and stratigraphic sequence are of overriding importance in any Tier 3 assessment. More extensive information becomes necessary if numerical modeling is proposed.

- Name and type (confined/unconfined) of aquifer(s) from which water supply well produces.
- Natural hydraulic gradient (when pump is not running and cone of depression has disappeared.)
- Textural nature of the aquifer (e.g., matrix or fracture porosity and percentage).
- Hydrologic parameters of the stratigraphic units (e.g., vertical hydraulic conductivity ( $K_v$ ), horizontal hydraulic conductivity ( $K_h$ ), fraction of organic carbon ( $F_{oc}$ ).
- Lithologic descriptions. Thicknesses and order of all stratigraphic units between ground-surface and base of aquifer of interest.
- Designation of stratigraphic units known to confine or partially confine aquifer of interest (See Table 1.)
- Aquifer vulnerability according to IGS criteria.
- Contaminated zone location and dimensions.

The table below is an example of a designation of stratigraphic units as mentioned in the above list.

**Table 1.**  
Example stratigraphic designation for a project area.

Depth range	Unit	Hydrologic character
Surface to ± 30 feet	Holocene alluvium	Unconfined aquifer, unconsolidated silt & clay near surface, sandier with depth. $0.5 < K_h < 1.5$ m/d in sandier portion.
± 30 ft to ±50 ft	Pleistocene clay	Confining unit, present throughout valley, no known measurement of $K_h$ or $K_v$ .
±50 ft to ±120 ft	Pleistocene outwash	Confined aquifer, sequence of unconsolidated, graded units with gravel at base and fine sand at top. $50 < K_h < 80$ m/d.
>120 ft (max depth of concern in this project)	Ordovician Maquoketa Fm.	Confining unit, consolidated shale with thin carbonate interbedded near top. Thickness > 100 ft in area.

Information about hydrostratigraphy in the vicinity of the contamination source and at-risk well might be obtained from the following sources:

- Iowa Geological Survey.
- U.S. Geological Survey.
- Iowa Rural Water Association.
- Private site assessment reports (e.g. inhouse engineering report).
- DNR UST or Contaminated Sites Section files.
- EPA CERCLA files.
- Local well driller.
- Water resource journals (e.g. *Ground Water*, *Journal of Hydrology*, *Ground Water Monitoring & Remediation*).
- Graduate theses and dissertations at universities.

**Demonstrating a water supply well not at risk from a contamination source**

The assessment techniques given below are suggestions only, and should not be taken as limitations or required approaches for Tier 3 work. Approaches necessarily differ for situations I and II or III (above). The groundwater professional must realize the three situations presented will not represent all possible situations for water supply wells. The applicability of each technique to one or more of the three example situations is noted by Roman numerals in parentheses. Some techniques provide information about well vulnerability. Other techniques provide information about well radius of influence or well construction and integrity. The Tier 3 Work Plan must state which of these concerns are part of the assessment. Additional information concerning the Work Plan is found in Section 2.

A complete Tier 3 assessment might utilize several techniques. The goal of Tier 3 assessment is to demonstrate that, at a minimum, contaminant concentrations at the receptor will not exceed the chemical of concern concentrations in the Tier 1 Look-up Table (567 IAC 135). Where soil and water sampling are needed, it is incumbent on the groundwater professional to employ proper sampling and analytical protocols. **Results of the techniques employed, combined with information about current contamination situation, site history, well construction, pumping rate and schedule, and hydrostratigraphy, are to be discussed in the Tier 3 Report.** The results form the basis for the groundwater professional's recommendation to DNR concerning the site. Additional information concerning the Tier 3 Report is found in Section 2.

1. Well Vulnerability (II, III): Compare static water levels (SWLs) from site monitoring wells ( MWs) and the water supply well. If a confining layer or perched aquifer separates the water producing interval from the contaminated zone, SWLs from the aquifers above and below the confining layer will likely differ markedly. More information is needed to make a conclusive case, however. If there is a gradient downward across the confining layer, under **static or pumping** conditions, the confined aquifer might not be protected from contamination. If there is a constant upward gradient across the confining layer, under static and pumping conditions, the confined aquifer is likely protected from contamination. Demonstration of differing SWL's (i.e., upward hydraulic gradient or artesian condition), together with evidence of plume stability supports the case that the well is not at high risk under existing conditions.
2. Well Vulnerability (II, III): Compare major ions and other water properties from unconfined and confined aquifers. If a confining layer or perched zone separates the water producing interval from the contaminated zone, water samples from the different saturated intervals might show differences in major ion composition. The ions of interest are:  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{HCO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ , and silica. Other water properties that should be measured at time of collection are pH, color, and temperature. Analytical results may be compared in the Tier 3 Report by any of several graphical techniques, for example: Piper diagrams, Collins bar charts, Stiff diagrams, or pie charts (see Hem, 1985), or Schoeller graphs (see Fetter, 1994). Demonstration of differing major ion chemistry between water in the contaminated layer and water pumped from the well, together with evidence of plume stability, supports the case the water supply well is not at risk under existing conditions.
3. Well Vulnerability and Casing Integrity (II, III): Sample for tritium, nitrate, and petroleum from site MWs and the water well. These substances have sources at or near the ground surface; so groundwater in aquifers protected by an aquitard are expected to show only background concentrations. If a tritium concentration of ~1 TU is found in an aquifer, isolation of the well from contamination is supported. Dilution in a well can mask a tritium or nitrate signal, so **background-level tritium or nitrate concentrations alone are not sufficient to demonstrate well protection from petroleum contamination**, but the two together do strengthen the case for lower risk, and can be considered part of a body of evidence when considered with

independent information such as differing SWLs or differing major ion compositions as in techniques 1 or 2. Note: If the water supply well is within 100 feet (or 1,000 feet for granular or nongranular bedrock sites or 1 mile for a public water supply) of an actual groundwater contamination plume, it must be sampled for petroleum contamination.

4. Well Vulnerability and Radius of Influence (I, II, III): Monitor SWL in critically located observation wells during normal pumping cycle of water well. For each of the three situations it is possible to determine whether the pumping well induces a hydraulic gradient that could move contamination toward the well intake. This is accomplished by utilizing existing wells and by placing nested observation wells between the water supply well and the contaminated zone. Water levels in a line of wells extending from the pumping well to the monitoring wells in the contaminated zone are monitored during a typical daily (24 hr.) pumping cycle. In certain situations it might be desirable for the observation period to extend over 120 hours of pumping at maximum capacity. For this type of test it is also necessary to know how daily changes in barometric pressure affect water levels in the wells, and to monitor barometric pressure and water level in a control well throughout the test. Daily water level fluctuations induced by barometric pressure changes can be greater than 0.1 feet, and might obscure any water level changes due to the pumping well. If no appreciable induced gradient is evident from the monitoring data, it is reasonable to conclude the well will not capture the contamination. This information, together with evidence of plume stability outside the radius of influence, indicates neither natural advection nor pumping-induced gradients will transport contamination to the capture zone of the water supply well, and thus the water supply well is not at high risk under current conditions.
  
5. Well vulnerability (I, II, III): Determine site-specific fate and transport parameters, and model analytically. For any situation involving horizontal advection in an aquifer characterized using Darcy's Law, if it is important to show contamination will not reach the well location (open hole, screened, or cased interval), the three-dimensional analytical fate and transport model of Domenico (1987) can be used, provided defensible values are obtained for a steady-state gradient and for the following site-specific parameters:

Source concentration ( $C_0$ ) of the chemical of concern.

Source dimension width ( $Y$ ) and depth ( $Z$ ) transverse to gradient direction.

Horizontal hydraulic conductivity ( $K_h$ ).

Decay rate ( $\lambda$ ) of the chemical of concern.

Adsorption coefficient ( $K_d$ ) of the chemical of concern.

Longitudinal dispersivity ( $\alpha_x$ ) of the chemical of concern.

**With good quality site data, Domenico's 3-D solution to the advection-dispersion-reaction equation may be solved to demonstrate maximum transport**



**distance and travel- time of the chemicals of concern under a constant hydraulic gradient through a homogeneous aquifer. If site conditions differ at all from invariance and homogeneity, analytical modeling might not be appropriate.** The groundwater professional must convincingly justify any assumptions made to simplify a site for such modeling. Discussion of model sensitivity to parameter uncertainty must be included in the Tier 3 Report. This technique is a more detailed and theoretically rigorous form of the analytical model employed in the DNR Tier 2 software. Modeling results showing contamination will not reach the well at concentrations above the Tier 1 Look-up Table concentration, even for the cases with extreme values of poorly-constrained parameters, is evidence against a high risk condition.

6. Well Vulnerability and Radius of Influence (I, II, III): Perform a pumping test on the water supply well. With observation wells installed at differing distances between the pumping well and the contamination source, a pumping test can be designed to demonstrate the radius of influence of the well for situations similar to I, II, and III, and to determine whether the aquitard is leaky for situations like II. Pumping test duration should be at least 24 hours for situations like I and III, and 120 hours to test for a leaky aquitard. Consult standard groundwater references for more details on pumping tests (e.g., Driscoll, 1986; Dawson and Istok, 1991). Demonstrating contamination is not within the well radius of influence, together with evidence of plume stability indicates the water supply well is not at high risk under current conditions.
7. Casing Integrity (II, III): Use a borehole televiewer and/or casing pressure testing to check for breaches in the water supply well casing. When the cost is justified, these methods might be considered. Drillers have reported pressure testing is rare for wells of diameter greater than 12 inches. Both methods involve removing the pump and tubing for the test. Demonstration of casing integrity through a contaminated layer, together with evidence that the well is properly sealed and does not draw water from the contaminated layer supports the case the well is not at high risk under current conditions.
8. Well Vulnerability and Radius of Influence (I, II, III): Determine site-specific fate and transport parameters (see no. 5, above) and employ numerical modeling software. Numerical models consist of two parts: the flow model and the fate and transport model. The entire modeling exercise requires input of many parameters. The parameters must be accurate representations of site conditions. Both the flow and transport models must be calibrated and sensitivity tested. All this be documented in a Tier 3 Report. The fundamental requirement is that the model accurately represents actual hydrogeology of the site. Calibrated modeling results showing the water supply well will not be contaminated above the Tier 1 Look-up Table concentration, even for the cases with extreme values of poorly-constrained parameters, is evidence against a high risk condition. The modeler's credentials should be included in the Tier 3 Report (see Section 2).

## SECTION 2.

### **Requirements for work plans and reports involving numerical modeling**

The groundwater professional expected to present in a Tier 3 Work Plan evidence showing what the situation is concerning an at-risk water well, and to detail how well-vulnerability will be conclusively determined. Chapter 135 states:

“...Prior to conducting a Tier 3 assessment, a groundwater professional must submit a work plan to the department for approval. The work plan must contain an evaluation of the specific site conditions which justify the use of a Tier 3 assessment, an outline of the proposed Tier 3 assessment procedures and reporting format and a method for determining a risk classification consistent with the policies underlying the risk classification system in 135.12(455B). Upon approval, the groundwater professional may implement the assessment plan and submit a report within a reasonable time designated by the department.” [567 IAC 135.11(1)].

### The Tier 3 Work Plan

#### *General requirements*

In order to receive approval of the Tier 3 Work Plan, the groundwater professional must provide information on the nature of the problem, a statement on the reliability of the assessment methods proposed, and the step-by-step procedure that will yield a reliable assessment of risk to a water supply well (or any high risk receptor). Listed below are essential points that must appear in any Tier 3 Work Plan.

1. Name of the certified groundwater professional who will be the project manager.
2. Correct LUST site address, including street or 911 number, community, Section-Township-Range designation, County.
3. List of high risk pathways for the site and chemicals of concern for each pathway.
4. Short discussion of reasons for each high risk pathway.
5. Identification of each receptor to be evaluated at Tier 3, and justification of the proposed assessment strategy for each including the specific site conditions which support the use of a Tier 3 assessment.
6. Identification and discussion of any high risk receptors requiring corrective action for which the Tier 3 assessment will not apply, and how the high risk factors to these receptors will be reduced.

7. Statement of sampling, analysis, and QA/QC protocols, and procedures for any other site activities (e.g., geophysical survey, penetrometer) planned as part of the Tier 3 assessment. Because the groundwater and soil sampling in a Tier 3 assessment differs from that in Tier 1 and Tier 2, a detailed statement of the sampling method is important to ensure valid samples and analytical results will be obtained.
8. Scaled site map showing locations of contamination sources and all receptors.
9. Scaled site map and geologic cross section showing proposed sample points. Include water well construction diagram if already obtained.
10. Discussion of how the Tier 3 assessment will determine risk.

*Special requirements for numerical modeling*

The use of numerical modeling programs for Tier 3 assessment requires much more information than other techniques do. This is because the potential for gross error or incorrect yet plausible results is high. In other words, whenever computer programs are employed the problem of “garbage-in, garbage-out” exists. Therefore, any groundwater professional proposing to employ numerical modeling must demonstrate competence, experience with the software, and thorough understanding of what a conclusive result will look like. Listed below are points that must appear in a work plan involving numerical modeling.

1. Name of the modeler and modeler’s hydrogeological qualifications and relevant experience. Examples of modeler’s previous projects demonstrating successful use of software proposed for current Tier 3 activity.
2. Identification of the software to be used in the Tier 3 assessment. Discussion of how the Tier 3 assessment will determine risk. Statements of 1) how a favorable modeling result will be used to justify a recommendation a high risk designation be reduced; 2) what actions are contemplated to resolve high risk conditions resulting from an adverse modeling result.
3. Statement of which site parameters critical to model validity are reasonably well-constrained, and which have uncertainty that will require careful sensitivity analysis. Discussion and justification of the values selected for uncertain parameters, and any sampling intended to provide better knowledge of parameter values. Discussion of the case expected to be most likely, and cases using extreme but reasonable values for poorly-constrained parameters.
4. List of all modeling information (input and output) that will appear in the Tier 3 Report. This must include designations of domain boundary types and justifications for each boundary; designations of differing layers and areal zones expected, and justifications for each; tables of calibration results for the flow model and for the fate and transport model; tables of parameter ranges and pertinent results from all sensitivity analyses.
5. A project schedule with each general work item (e.g., drilling-sampling-analysis, model set-up, report writing) tied to starting and completion dates.

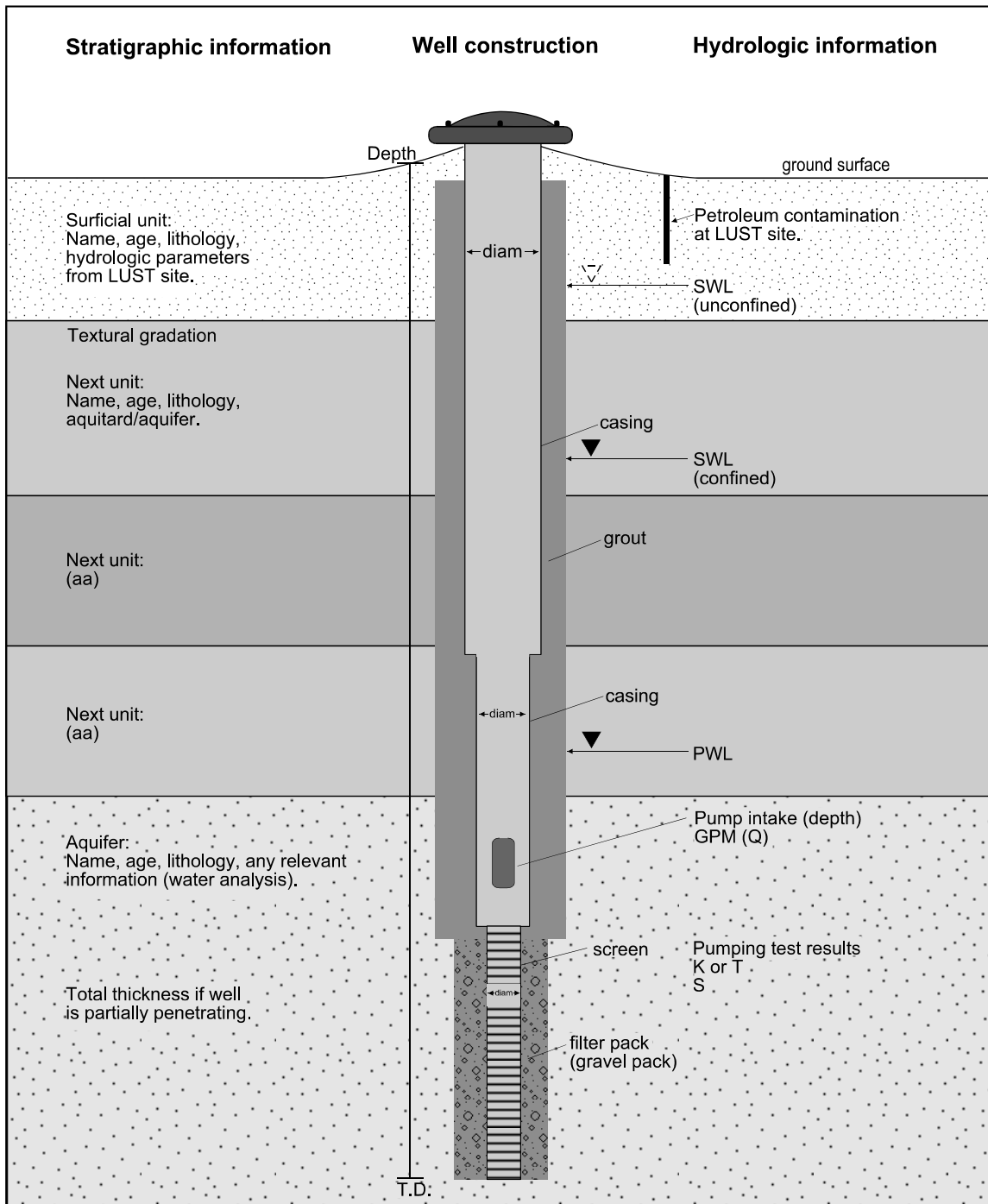
## The Tier 3 Report

### *General requirements*

The report must echo the work plan and clearly state the nature of the high risk condition to the receptor of concern. The report must also present details of the Tier 3 assessment clearly and completely. Discuss how the results are conclusive. When a pumping test or casing pressure test is performed, all raw data acquired must be included in the report. When a televiwer survey is performed, a copy of the video record must accompany the report.

A diagram is required showing the well construction in depth-scaled cross-section adjacent to a representation of the hydrologic information and the geologic section with stratigraphic units arranged correctly by depth. An example is shown in the following figure:

## Example Well Diagram



WellDiagram.cdr

### *Special requirements for numerical modeling*

Guidance in report content for numerical modeling generally follows the recommendations given in Anderson and Woessner (1992). Anyone seeking further discussion of report preparation should consult Chapter 9 of that text. Reports involving

numerical modeling must be information-rich. All assumptions, conclusions and recommendations must be thoroughly and explicitly justified.

To be conclusive, a numerical modeling report must: 1) demonstrate calibration of the model to actual site conditions; 2) illustrate and discuss sensitivity of modeling results to reasonable ranges of poorly-constrained parameters; and 3) yield an estimate of risk that can be related in a straightforward manner to the Site Specific Target Levels (SSTL) values used in RBCA.

A suggested report outline is given below. In some cases, additional information may be necessary to convey a complete understanding of the groundwater model.

- Title page
- Table of contents
- List of figures
- List of tables
- Executive summary
  
- Introduction
- Project objectives (risk pathways, SSTL)
- Hydrogeologic characterization of the site
- Conceptual model
- Model design and input parameters
- Model calibration
- Sensitivity analysis
- Predictions or evaluation of remedial alternatives
- Conclusions and recommendations
  
- References
- Tables
- Figures
- Well information
- Additional pertinent information

In reporting on modeling results, the modeler should describe the work in sufficient detail so the model reviewer may determine the appropriateness of the model for the site problem simulated. The report must detail the processes by which the modeling software was selected and by which the model was conceptualized, developed, calibrated, verified and utilized. Limitations of the model must also be discussed, and the decision to employ a transient or steady-state model must be justified. All hydrogeological data used to characterize the site must be presented. Justification must be made for all hydrologic assumptions and for selection of any unmeasured parameter values (e.g., dispersivities, recharge, stream bed conductance). Calculations must be presented for all derived parameters used in the model (e.g., retardation factors, biodegradation rate constants) so the reviewer may reproduce the values employed.

Justification must be given for the ranges of error selected in the calibration process for both the flow model and the fate and transport model. Discussion must be given describing the process by which parameter values are adjusted to achieve model

calibration. The sensitivity analysis must convey to the reviewer what the model predicts if poorly-constrained parameters take their extreme values.

Tables and illustrations should be liberally employed in the modeling report, and must include:

1. Site map.
2. Site hydrostratigraphic cross section.
3. Conceptual model in map and cross section views.
4. Map of the model grid including contaminant source dimension, receptor location, calibration points.
5. Site maps and cross sections showing latest contaminant sampling results and groundwater elevations.
6. Maps, cross sections and tables of model predictive results for scenarios of interest (e.g., no further action, source removal, increased pumping rate, active groundwater control), and for ranges of reasonable values for poorly-constrained parameters.
7. Graphs and tables of calibration data for flow model and fate and transport model.

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