Groundwater Classification

Objectives: This document provides recommended procedures for classifying groundwater and documenting the classification under the Texas Risk Reduction Program.

Audience: Regulated Community and Environmental Professionals

References: The Texas Risk Reduction Program (TRRP) rule, together with conforming changes to related rules, is contained in 30 Texas Administrative Code Chapter 350. The TRRP rule was initially published in the September 17, 1999 Texas Register (24 TexReg 7413-7944). The rule was amended in 2007 (effective March 19, 2007; 32 TexReg 1526-1579) and 2009 (effective March 19, 2009; 34 TexReg 1861-1872).

Find links for the TRRP rule and preamble, Tier 1 PCL tables, and other TRRP information at: <www.tceq.state.tx.us/remediation/trrp/>.

TRRP guidance documents undergo periodic revision and are subject to change. Referenced TRRP guidance documents may be in development. Links to current versions are at: <www.tceq.state.tx.us/remediation/trrp/guidance.html>.

Contact: TCEQ Remediation Division Technical Support Section: 512-239-2200, or <techsup@tceq.state.tx.us>.

For mailing addresses, refer to: <www.tceq.state.tx.us/about/directory/>.

1.0 Introduction

This document discusses the rule requirements for groundwater classification and provides a recommended process for completing groundwater classifications.

1.1 Applicable Regulatory Requirements

Under the Texas Risk Reduction Program (TRRP) rule, all groundwater-bearing units affected by, or reasonably anticipated to be affected by, chemicals of concern (COCs) having concentrations at or above residential groundwater assessment levels must be characterized with regard to the applicable groundwater resource classification, in accordance with §350.52. Under §350.4(a)(40), a groundwater-bearing unit is defined as a saturated geologic formation, group of formations, or part of a formation that has a hydraulic conductivity equal to or greater than 1 x 10^-5 cm/sec.

TRRP at §350.52 establishes three categories of groundwater resources, designated Class 1, Class 2, and Class 3, based upon a site-specific evaluation of the current use of the groundwater-bearing unit (GWBU), as well as its potential use, as defined on the basis of natural water quality and well yield (see Table 1).
Saturated geologic units can be identified most readily during assessment by their capability to transmit water to an open borehole. Only saturated geologic units with hydraulic conductivities of \( K \geq 1 \times 10^{-5} \text{ cm/sec} \) meet the definition of groundwater bearing unit (GWBU) in §350.4(a)(40) and must be classified as Class 1, Class 2, or Class 3 groundwater. Saturated geologic units with hydraulic conductivities of \( K < 1 \times 10^{-5} \text{ cm/sec} \) are not subject to the classification requirements of §350.52.

### 1.2 Key Acronyms and Abbreviations

- APAR: Affected Property Assessment Report
- ASTM: American Society for Testing and Materials
- COC: Chemical of concern
- gpd: Gallons per day
- GWBU: Groundwater-bearing unit
- K: Hydraulic conductivity
- PCL: Protective concentration level
- PDWS: Primary Drinking Water Standards
- PWS: Public water supply
- Q: Well yield (e.g., from well)
- RAL: Residential assessment level
- TDS: Total dissolved solids
- TCEQ: Texas Commission on Environmental Quality
- TRRP: Texas Risk Reduction Program
- USCS: Unified Soil Classification System

### 1.3 Effect of Groundwater Resource Classification on TRRP Response Objectives

For each affected GWBU, the applicable groundwater response objectives, including the types of response measures that may be applied (removal/decontamination vs control) and the associated residential assessment level and groundwater protective concentration level (PCL), depend upon the groundwater resource classification of that GWBU and any other GWBUs which may be hydraulically-interconnected with it (See Sections 2.1.2 and 2.4) to the degree that it potentially can be impacted.
Applicable remedy standards and exposure pathways for Class 1, Class 2, and Class 3 groundwater resources are described below.

1.3.1 Applicable Remedy Standards

Under TRRP, the person conducting the response action may implement either Remedy Standard A (requiring removal or decontamination of affected media such that COC concentrations are less than or equal to applicable PCLs) or Remedy Standard B (requiring removal, decontamination, or control of affected media so as to prevent exposure to COCs at levels exceeding applicable PCLs). The applicability of removal/decontamination or control often is dictated by the groundwater resource classification, as follows:

1.3.1.1 Class 1 Groundwater.

For Class 1 groundwater resources, affected groundwater must be removed and/or decontaminated to the critical PCL; control options are not permitted by §350.33(b).

1.3.1.2 Class 2 or 3 Groundwater.

For affected Class 2 or Class 3 groundwater resources, affected groundwater must be removed and/or decontaminated to the critical PCL, unless: a plume management zone is approved per Remedy Standard B (§350.33), or such remediation is demonstrated by the person to be technically impracticable, in which case a plume management zone is required.

1.3.1.3 Groundwater Classification using Table 1.

Table 1 summarizes the TRRP Groundwater Resource Classification System by regulatory citation. Classification of a groundwater resource may be based on its potential use and/or its current use. A GWBU is assigned the highest water-quality classification for which all of a citation’s applicable potential use and current use conditions are true. However, different classifications can apply to different portions of a single GWBU. For example, a GWBU can transition laterally from Class 2 to Class 3. Additionally, response objectives for each affected GWBU must be adjusted as needed to be protective of any hydraulically-interconnected GWBUs to which COCs could migrate such that the pathway can be reasonably anticipated to be complete (§350.71(c)).
1.3.2 Applicable Groundwater Exposure Pathways and PCLs

Under TRRP, a set of groundwater PCLs apply, at a minimum, to affected groundwater contained within GWBUs. The applicable groundwater exposure pathways and associated groundwater PCLs depend upon the site-specific groundwater resource classification and applicable exposure conditions, as follows:

Discussion Box
This discussion addresses GWBUs only. In some cases, additional response objectives may apply to soil strata based on other relevant soil PCLs, or non-aqueous phase liquids. Refer to the TCEQ document Affected Property Assessment Requirements (RG-366/TRRP-12) for additional discussion of applicable soil exposure pathways.

1.3.2.1 Class 1 and 2 Groundwater Ingestion Pathways.

All Class 1 and Class 2 groundwater resources are considered usable, or potentially usable, drinking water supplies. Therefore, under TRRP, the groundwater ingestion exposure pathway \( ^{GW}G_W^{Ing} \) is applicable to Class 1 or Class 2 groundwater.

1.3.2.2 Class 3 Groundwater Resource Protection Pathways.

Class 3 groundwater resources are not considered usable as drinking water and are not subject to groundwater ingestion PCLs. Rather, Class 3 groundwater is subject to the \( ^{GW}G_W^{Class 3} \) PCL, which is equal to \( 100 \times ^{GW}G_W^{Ing} \).

A decision-logic flowchart for determining groundwater resource classification is provided on Figure 1.

1.3.2.3 Additional Exposure Pathways.

For Class 1, Class 2, or Class 3 groundwater resources, if either the groundwater-to-surface water exposure pathway \( ^{SW}G_W \) or the groundwater-volatilization-to-ambient air exposure pathway \( ^{Air}G_W^{inh-V} \) is determined to be complete, the PCL for the additional pathway(s) will apply.

NOTE: If a GWBU meets the criteria for more than one groundwater classification, then the GWBU shall be assigned the higher (quality) classification (§350.52).
<table>
<thead>
<tr>
<th>Groundwater Classification</th>
<th>TRRP Citation</th>
<th>Potential Use of GWBU Based on Aquifer Characteristics - Well Yield Criteria</th>
<th>Potential Use of GWBU Based on Aquifer Characteristics - Water Quality Criteria</th>
<th>Current Use of GWBU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1 Groundwater Resource</td>
<td>§350.52(1)(A)</td>
<td>&gt; 5,000 gpd (from 4-inch diameter well or equivalent)</td>
<td>TDS &lt; 1,000 mg/L</td>
<td>Affected GWBU is within 0.5 miles of an existing public water supply well and COCs could impact the groundwater production zone for the well.</td>
</tr>
<tr>
<td></td>
<td>§350.52(1)(B)</td>
<td>≥ 144,000 gpd (from 12-inch diameter well or equivalent)</td>
<td>TDS ≤ 3,000 mg/L and water meets PDWS</td>
<td>GWBU is the only reliable source of water in vicinity (i.e., no public water system available) and depth to unit ≤ 800 feet bgs.</td>
</tr>
<tr>
<td>Class 2 Groundwater Resource</td>
<td>§350.52(2)(A)</td>
<td>&lt; 144,000 gpd (from 12-inch diameter well or equivalent) and ≥ 150 gpd (from 4-inch diameter well or equivalent)</td>
<td>TDS ≤ 10,000 mg/L</td>
<td>No current use required</td>
</tr>
<tr>
<td></td>
<td>§350.52(2)(B)</td>
<td></td>
<td></td>
<td>Affected GWBU is groundwater production zone for an existing well (other than public water supply well) located within 0.5 miles of affected groundwater and used either for human consumption, agriculture, or other purpose that could result in human or ecological exposure.</td>
</tr>
<tr>
<td>Class 3 Groundwater Resource</td>
<td>§350.52(3)(A)</td>
<td>&lt; 150 gpd (from 4-inch diameter well or equivalent)</td>
<td></td>
<td>Groundwater from affected GWBU is not used within 0.5 miles in a manner resulting in human or ecological exposure.</td>
</tr>
<tr>
<td></td>
<td>§350.52(3)(A)</td>
<td></td>
<td>TDS &gt; 10,000 mg/L</td>
<td>Groundwater from affected GWBU is not used within 0.5 miles in a manner resulting in human or ecological exposure.</td>
</tr>
</tbody>
</table>

bgs = below ground surface.  
gpd = gallons per day.  
COC = chemical of concern.  
GWBU = Groundwater-Bearing Unit.  
PDWS = Primary Drinking Water Standards per 40 CFR Part 141.  
TDS = Total Dissolved Solids.  
Groundwater Production Zone – the groundwater-bearing unit(s) which contributes water to a well (see Section 2.5.2.1).
Figure 1. TCEQ Groundwater Resource Classification Logic Diagram.
1.4 Use of this Guide for Classifying Groundwater Resources

The following sections of this guide present step-by-step procedures to determine the appropriate groundwater classification for each GWBU. *In general, the level of effort required for this classification process will depend upon the type of classification to be demonstrated.*

1.4.1 Known or Default Class 1 Groundwater Resource

*By default, a GWBU has a Class 1 designation unless it can be demonstrated otherwise* using the classification process described herein. If the affected GWBU is known to be a public drinking water supply aquifer (e.g., Edwards, Ogallala, Evangeline, etc.), then the applicable resource designation is probably Class 1 and no further evaluation of the resource classification is necessary *unless* the person intends to demonstrate that the affected portion of that GWBU is a zone of lower productivity or water quality. However, assessment and characterization of all affected or threatened GWBUs should be submitted via the APAR. Similarly, if the affected GWBU is not a producing zone for a public drinking water supply well, but the person is prepared to conduct the response action consistent with the response objectives applicable to a Class 1 groundwater resource, then a Class 1 designation may be assumed without further demonstration. Table 2 summarizes the criteria by which a Class 1 groundwater resource designation is made.

Reclassification of a groundwater resource to a lower classification (e.g., reclassify from Class 1 to Class 2) may be appropriate in instances when: 1) site conditions change, 2) when the person wishes to amend a Class 1 default classification, or 3) any other circumstance under which reclassification is appropriate. However, reclassification to a lower classification resource shall require submittal of all commensurate data associated with the amended classification (see Section 2.9).
Table 2. Class 1 Groundwater Resource Criteria

<table>
<thead>
<tr>
<th>Case</th>
<th>Resource Use</th>
<th>Groundwater Quality</th>
<th>Well Yield (Productivity)¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Class 1 designation assumed by default</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Case 2</td>
<td><strong>Class 1 Use Criteria</strong></td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Affected GWBU is within 0.5 miles of PWS well and COCs could migrate to groundwater production zone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 3</td>
<td><strong>Class 1 Use Criteria</strong></td>
<td>TDS &lt;1,000 mg/L</td>
<td>Q &gt; 5,000 gpd</td>
</tr>
<tr>
<td></td>
<td>GWBU is only reliable source of water in area and</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Depth &lt; 800 feet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 4</td>
<td><strong>Class 1 Use Criteria</strong></td>
<td>TDS ≤ 3,000 mg/L</td>
<td>Q ≥ 144,000 gpd</td>
</tr>
<tr>
<td></td>
<td>No required use</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

gpd = gallons per day  \hspace{1cm} mg/L = milligrams per liter

PDWS = primary drinking water standard  \hspace{1cm} PWS = public water supply

Q = well yield \hspace{1cm} TDS = total dissolved solids

¹Well yield determined via Methods 1 and 2 (see Section 2.7).

1.4.2 Class 2 Groundwater Resource

To show that an affected GWBU is a Class 2 groundwater resource, the person need only demonstrate that the unit does not currently qualify as a Class 1 resource. This demonstration requires, at a minimum, an accurate and thorough water well survey that identifies all water wells within 0.5 miles of the extent of affected groundwater, and if the survey reveals there is no use within 0.5 miles:

1. an evaluation of water quality, or

2. an estimate of well yield for the affected GWBU.

As indicated in Figure 1, a Class 2 designation may be applied to GWBUs that do not meet the Class 1 criteria. Table 3 summarizes the criteria by which a Class 2 groundwater resource designation is made.
Table 3. Class 2 Groundwater Resource Criteria

<table>
<thead>
<tr>
<th>Resource Use</th>
<th>Groundwater Quality</th>
<th>Well Yield (Productivity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class 2 Use Criteria</td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Production zone for existing water supply well (other than PWS well) within 0.5 mile &amp; used for human consumption, agriculture, etc.</td>
<td>Brackish 3,000 mg/L &lt; TDS (\leq) 10,000 mg/L (and may not meet PDWS)</td>
<td>Moderate or High (Q \geq 150) gpd</td>
</tr>
</tbody>
</table>

1. Well yield determined via Methods 1 and 2 (see Section 2.7).

PDWS = primary drinking water standard
PWS = public water supply
Q = well yield
TDS = total dissolved solids

1.4.3 Class 3 Groundwater Resource

To show that an affected groundwater-bearing unit is a Class 3 groundwater resource, the person must demonstrate that the unit does not currently qualify either as a Class 1 or Class 2 resource. This demonstration comprises a more rigorous site-specific evaluation than is required for a Class 1 or Class 2 designation. At a minimum, the person must provide all site-specific data required for a Class 2 groundwater determination plus the following supporting information:

1. site-specific natural TDS of the affected groundwater-bearing unit \(>\) 10,000 mg/L, or

2. determination that the sustainable daily rate of withdrawal from a properly completed well is less than 150 gpd using Method 1 or Method 2 (see Section 2.7 and 2.8).

Table 4 summarizes the criteria by which a Class 3 groundwater resource designation is made. As shown, well yield is the critical classification criterion for Case 1 and Case 2. Groundwater quality is the critical criterion for Case 3, Case 4, and Case 5.

1.4.4 Saturated Soils

As defined by the TRRP rule, saturated geologic units with a hydraulic conductivity \(K < 1 \times 10^{-5}\) cm/sec do not qualify as GWBUs for purposes of requisite GWBU classification. At a minimum, the person must provide the following supporting information:

1. site-specific evaluation of hydraulic conductivity (required), and

2. laboratory-determined USCS soil classification.
<table>
<thead>
<tr>
<th>Resource Use</th>
<th>Groundwater Quality</th>
<th>Well Yield (Productivity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>No well use</td>
<td>N/A</td>
</tr>
<tr>
<td>Case 2</td>
<td>No well use</td>
<td>TDS ≤ 10,000 mg/L</td>
</tr>
<tr>
<td>Case 3</td>
<td>No well use</td>
<td>TDS &gt; 10,000 mg/L</td>
</tr>
<tr>
<td>Case 4</td>
<td>No well use</td>
<td>TDS &gt; 10,000 mg/L</td>
</tr>
<tr>
<td>Case 5</td>
<td>No well use</td>
<td>TDS &gt; 10,000 mg/l</td>
</tr>
</tbody>
</table>

1Well yield determined via Methods 1 and 2 (see Section 2.7)  
gpd = gallons per day
PDWS = primary drinking water standard  
Q = well yield
TDS = total dissolved solids

2.0 Principal Steps in Groundwater Resource Classification Process

To establish the appropriate groundwater resource classification, the person must first identify the GWBUs that have been affected (or could reasonably be expected to be affected) by a COC in excess of the applicable residential assessment level (RAL). See TCEQ guidance document Affected Property Assessment Requirements (RG-366/TRRP-12) for information on COC assessment. Since the applicable RAL is determined on the basis of the groundwater classification, the groundwater COC assessment and groundwater classification procedures often will be iterative. However, a preliminary evaluation of background information on local hydrogeology and groundwater use may give the person an indication of the likely GWBU classification before initiating a drilling program. Since the assessment level is the same for Class 1 and Class 2 groundwater, but is different for Class 3 groundwater, the critical consideration is whether the GWBU is likely Class 3.

Therefore, before following the steps outlined in this section, it is recommended that the on-site groundwater COC assessment be completed at a minimum. Particular attention should be given to recognition of any natural preferential groundwater transport pathways for the COCs as these indicate zones that should be focused upon when characterizing a GWBU. Note that even if the on-site COC assessment indicates that groundwater is not yet affected, the upper-most GWBU still must be classified in order to set soil PCLs that are protective for that upper-most GWBU. Alternatively, the unaffected upper-most GWBU can be presumed to be Class 1.
2.1 Overview of Classification Process

A groundwater-bearing unit is defined as a saturated geologic formation, group of formations, or part of a formation that has a hydraulic conductivity equal to or greater than $1 \times 10^{-5}$ cm/sec.

Groundwater resource classifications are determined on a site-specific basis, requiring hydrologic and geologic information for the GWBU under investigation. Available information from nearby sites may be used to augment the site-specific evaluation – but typically will not be acceptable as a substitute for requisite site-specific information.

In each step of the groundwater resource classification process, care must be taken to demonstrate that all information provided is representative of that GWBU. Significant lithologic and stratigraphic heterogeneities, and variability of measured aquifer parameters and water chemistry, should be considered and reconciled for the purpose of delineating GWBUs whose physical, chemical, geologic, and hydraulic properties are internally consistent with and representative of that unit.

For each affected GWBU, determination of the appropriate groundwater resource classification is achieved through an orderly progression of steps. Depending on the actual classification, some steps may be optional (see Section 2.2). Table 5 summarizes the steps for determination of the groundwater resource classification on a site-specific basis.

The Classification Steps are summarized as follows:

2.1.1 Step 1: Describe Affected Groundwater-Bearing Unit(s)

Identify groundwater-bearing units by:

1. characterizing the site-specific stratigraphy and relevant water-saturated units with soil borings and USCS soil classification; and
2. grouping the saturated stratigraphic units into the fewest number of GWBUs that is reflective of hydrogeologic conditions.

Depositional environment and hydrostratigraphic considerations should factor into these evaluations (see Sec 2.3).
2.1.2 Step 2: Determine Hydraulic Interconnectivity

Determine any hydraulic interconnectivity with other GWBUs by using:

1. stratigraphic methods, including detailed site stratigraphy, levels at which water is first encountered, and static water levels;
2. hydraulic methods to determine if water levels in one GWBU respond to pumping stresses in the other GWBU, and/or
3. water chemistry methods, including affected groundwater and natural water quality tracers.

Table 5. Summary of Steps in Groundwater Resource Classification

<table>
<thead>
<tr>
<th>Procedures</th>
<th>Section</th>
<th>Notes</th>
<th>Required and Optional Classification Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify and define GWBU</td>
<td>2.3</td>
<td></td>
<td>Class 1 Class 2 Class 3 Sat. Soil</td>
</tr>
<tr>
<td>Describe Affected GWBUs or Saturated</td>
<td></td>
<td></td>
<td>■   ■   ■   ■</td>
</tr>
<tr>
<td>Soil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Determine Hydraulic Interconnectivity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stratigraphic method</td>
<td>2.4</td>
<td>Important if proving no threat to groundwater production zone</td>
<td>■   ■   ■   ■</td>
</tr>
<tr>
<td>Water chemistry method</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic method</td>
<td></td>
<td></td>
<td>■   ■   ■   ■</td>
</tr>
<tr>
<td>Field reconnaissance</td>
<td>2.5</td>
<td></td>
<td>■   ■   ■   ■</td>
</tr>
<tr>
<td>Determine Current Groundwater Use</td>
<td></td>
<td></td>
<td>■   ■   ■   ■</td>
</tr>
<tr>
<td>Records search *</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluation Natural Groundwater Quality</td>
<td></td>
<td>Important if not assuming Class 1</td>
<td>□   □   □   N/A</td>
</tr>
<tr>
<td>Determination of TDS</td>
<td>2.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluate GWBU Productivity</td>
<td></td>
<td></td>
<td>□   □   □   ■</td>
</tr>
<tr>
<td>Determine GWBU aquifer parameters or well yield</td>
<td>2.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluate GWBU Sustainability</td>
<td></td>
<td>Important if classification not based on wells or TDS</td>
<td>N/A □ N/A N/A</td>
</tr>
<tr>
<td>Ephemerality of saturation</td>
<td>2.8.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaluate GWBU Sustainability</td>
<td></td>
<td>Important if classification not based on wells or TDS</td>
<td>N/A □ N/A N/A</td>
</tr>
<tr>
<td>Hydrostratigraphic extent of GWBU</td>
<td>2.8.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 7 Document Results</td>
<td></td>
<td></td>
<td>■   ■   ■   ■</td>
</tr>
<tr>
<td>Reporting requirements</td>
<td>2.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Not required if GWBU is unaffected and assuming Class 1

■ = Required Step  □ = Optional Step

Revised March 2010
2.1.3 Step 3: Determine Current Groundwater Use

Identify current use of affected and interconnected GWBUs using:

1. field reconnaissance surveys within 500-foot radius of affected property; and
2. record searches for existing water supply wells within 0.5 miles in any direction from the affected groundwater zone.

2.1.4 Step 4: Evaluate Natural Groundwater Quality

Characterize natural water quality of GWBU(s) based on:

1. background TDS concentration, and
2. PDWS criteria (see 40 CFR Part 141) (optional).

2.1.5 Step 5: Evaluate GWBU Productivity

Determine aquifer and yield parameters of relevant GWBUs, including:

1. installation of fully-penetrating test wells appropriately screened and developed;
2. determination of GWBU hydraulic conductivities;
3. single- and multiple-well aquifer tests (optional for Class 1/Class 2 GWBUs); and
4. well yield tests (optional for Class 1/Class 2 GWBUs).

2.1.6 Step 6: Evaluate GWBU Sustainability

Characterize the sustainability of each GWBU to be classified, based on:

1. demonstration of historical or predicted permanence of saturation; and/or
2. analysis of the geologic extent and hydrologic character of GWBU.

2.1.7 Step 7: Document Results

Prepare for submittal all supporting documentation for the information upon which all groundwater resource classifications are determined. Submit the information and the results of the groundwater classification.
effort for TCEQ review as part of the Affected Property Assessment Report (APAR). Consider submitting the groundwater classification documentation for TCEQ approval prior to submitting the full APAR.

The appropriate content and format of the APAR is addressed in TCEQ Form No. 10325/APAR (see www.tceq.state.tx.us/remediation/trrp/guidance.html).

### 2.2 Required and Optional GWBU Classification Steps

Some steps in the groundwater resource classification process may be optional depending on the site-specific conditions or whether the Class 1 default is assumed. Table 5 summarizes the general minimum effort required for the classification of all affected GWBUs by indicating which classification steps are required or optional for completing the groundwater classification process.

For example, the classification process can conclude upon determination by the person that the affected GWBU could impact the groundwater production zone of a public water supply well or is the only reliable water supply source (i.e., Class 1 resource designation applies).

### 2.3 STEP 1: Describe Affected Groundwater-Bearing Units

Upon completion of a sufficient COC assessment, a site-specific hydrogeologic evaluation must be completed in order to characterize the stratigraphy over the depth and areal extent that soil and groundwater impacts have occurred, or could be expected to occur, and define GWBUs that must be classified. The stratigraphy should be evaluated in the context of the depositional environment in order that an appropriate hydrogeologic conceptual model is considered when defining the GWBUs.

Sampling locations and data collection methods must be sufficient to characterize the following:

1. depth of occurrence, lateral continuity, thickness, and geometry of soil or rock type of affected GWBUs;
2. saturated thickness; and
3. lateral extent and continuity of affected and interconnected GWBUs.

**Sealed Geoscience Work**

The description and interpretation of geologic units described herein qualifies as geoscience work (22 TAC §851.10). All boring logs, cross-sections, stratigraphic sections and maps depicting geoscience work must be individually sealed by a licensed professional geoscientist (P.G.) pursuant to 22 TAC §851.156.
2.3.1 Site Stratigraphy

The principal goal of the stratigraphic investigation for the affected property assessment is to characterize the occurrence and movement of groundwater affected or threatened by the COC release. The degree to which site stratigraphy is characterized should be based on the level of hydrogeologic complexity present at the location. The person should prepare for such an investigation by being familiar with the local geology prior to initiating an assessment in order to anticipate the full scope of the requisite work.

Stratigraphy must be correlated between different locations to define the continuity and thickness variation of each stratum across the site. At each location, the soil and/or rock column penetrated by the borehole should be discretized into individual strata based on variation of soil type, appearance, and apparent hydraulic properties. Standard stratigraphic correlation methods should be employed in constructing strike and dip sections for the site.

For the purpose of consistent stratigraphic characterization in the field and for presentation to the agency, soils observed and/or collected at the affected property should be classified according to the Unified Soil Classification System (USCS) per ASTM Standard Practice D 2488 (field classification method).

Supplemental subsurface information may be developed using cone penetrometer testing (CPT) or geophysical logging methods to generate continuous stratigraphic logs, based on appropriate correlation to actual soil or rock core samples from the site. Data from CPT and other logging methodologies can be used to supplement, but not replace, standard geologic log information (e.g., ASTM Standard Guide D 5434).

The number of borings necessary to satisfy a complete subsurface investigation should be commensurate with the size of the affected area(s) and the complexity of the hydrogeologic setting. The minimum number of borings is that necessary to satisfy the requirements of Section 2.3.

Various drilling and sampling methods may be employed for this purpose (e.g., hollow-stem auger, mud rotary, air rotary, etc.) as appropriate for...
local soil or rock conditions (see Attachment A for recommended drilling methods).

### 2.3.2 Identification of Water-Saturated Units

To qualify as a GWBU, a geologic formation (or a portion thereof) must be water-saturated and have sufficient hydraulic conductivity (i.e., $K \geq 1 \times 10^{-5} \text{ cm/sec}$).

Water saturation conditions within geologic strata can be confirmed on the basis of drilling observations, existing wells or piezometers, or installation of additional wells or piezometers. The presence of moisture or water seepage from soil cores, or water accumulation in boreholes during or after drilling operations suffices to confirm water saturation in a stratum.

For strata from which the presence of water saturation is difficult to discern during drilling (due either to low water yield rates, use of a wet drilling method, etc.), the presence or absence of water may be determined based upon inspection of an open borehole, piezometer, monitoring well, pore pressure transducer, or other reliable device that is capable of providing hydrologic information from an isolated stratum (or strata) in question and that is allowed to equilibrate for an appropriate time period following drilling or well installation (e.g., minimum 24-hour period for open borehole, piezometer, or monitoring well).

For unconfined saturated units, the depth at which water saturation occurs within the stratum can be defined based on the height of the static water level within the observation device. For confined units, the static water level will occur at or above the top of the permeable stratum, corresponding to fully saturated conditions within the permeable unit.

**Perched groundwater** is an unconfined zone of saturation formed above a main GWBU and is separated from the main GWBU by an unsaturated zone. Perched groundwater generally is maintained by a *perching bed*, or lens, of low hydraulic conductivity geologic material typically comprised of clay. If the perched groundwater exhibits Class 2 well yield characteristics, the zone may be downgraded to a Class 3 GWBU if it can be demonstrated that the unit has historically or predictably ephemeral saturation (see about Class 3 GWBUs, Sec. 1.4.3; and resource sustainability, Sec. 2.8).
2.3.3 Saturated Thickness

For unconfined GWBUs, the saturated thickness (b) at each location is the vertical distance from the static water level elevation to the base of the saturated unit. If static water level measurements are available for an extended time period for an unconfined GWBU, the static water elevation used for calculation of saturated thickness should be matched to the estimated mean annual static water level for the unit.

For confined GWBUs, the saturated thickness at each location is equal to the stratigraphic thickness of the GWBU, itself (i.e., the distance from the upper surface of the permeable stratum to its base).

Groundwater level measurements performed in accordance with ASTM Standard Test Method D 4750 are acceptable to the TCEQ.

If the GWBU is heterogeneous (e.g., consists of multiple soil types of variable hydraulic properties), refer to Section 2.3.4 for methods of organizing heterogeneous sediments into hydrogeologically coherent units.

The thickness of the saturated zone(s) beneath the affected property is recorded on geologic/soil boring logs and well logs, and should include both the level at which water was encountered and static water level measurements obtained from site monitoring wells, piezometers, or other appropriate measurement devices.

Groundwater levels that are observed to fluctuate over time should be measured over a period of time with a frequency sufficient to provide a statistically valid mean water level for each applicable GWBU.

Additional guidance on the collection, preparation, and presentation of groundwater-level information can be found in ASTM Standard Guide D 6000.

2.3.4 Characterization of Groundwater-Bearing Units

The characterization of GWBUs comprises: 1) the recognition of separate hydrostratigraphic units which possess contrasting hydraulic properties, and 2) the definition of the boundaries of hydraulically-distinct and separate GWBUs. Hydrostratigraphic units are comprised of geologic units grouped together on the basis of similar hydraulic conductivity (Fetter, 1988). The combination or separation of varied geologic materials into single, hydraulically-coherent GWBUs includes methodologies to:

1. delimit the boundaries of separate GWBUs based on hydraulic properties and the depositional environment which control the geometry of those geologic deposits, and

2. organize heterogeneous, anisotropic, rhythmic, or otherwise variable saturated geologic materials into GWBUs.
The delineation of separate GWBU sediments, performed in fulfillment of site characterization requirements for understanding COC distributions, should be placed within the context of their depositional environment and their applicable hydraulic properties. Guidelines for accomplishing the task of appropriately defining the boundaries of sedimentary GWBUs include the following:

1. Ensure the interpreted geometries of sediment bodies associated with zone(s) of saturation at the affected property are consistent with the general geologic framework.

2. Analyze site stratigraphy and assign all sediments associated with the zone(s) of saturation to an appropriate hydrostratigraphic unit.

3. Designate as a separate GWBU each saturated hydrostratigraphic unit that possesses unique bulk hydraulic properties.

4. Delineate the three-dimensional hydrostratigraphic boundaries comprising the affected or potentially impacted portion of each identified GWBU for the affected property.

5. Document the three-dimensional location and geometry of all identified and interconnected GWBUs and all intervening units (i.e., subsurface discontinuities, etc.) associated with the affected property.

Small-scale stratigraphic variations, such as thin alternating fine-grained/coarse-grained sequences may exist within a given GWBU (e.g., fluvial overbank deposits, coastal back-bay deposits, etc.). Since the coarse-grained sediments typically possess higher hydraulic conductivities and often act as the preferential COC transport pathways, it is necessary to group them appropriately when significant occurrences are observed. Small-scale sequences of interbedded sediment should be organized together into a single hydraulically-coherent GWBU when the following conditions are met:

1. the individual layers are too thin to practicably resolve their individual hydraulic properties using available aquifer testing methods; and

2. the bulk hydraulic property of a sub-section of the interlayered sequence is otherwise indistinguishable from the bulk hydraulic property of a different sub-section in the same sequence.

Large-scale stratigraphic units, such as homogeneous channel sand and beach sand bodies, which are sufficiently thick to practicably perform aquifer tests upon and which can yield meaningful measurements of aquifer hydraulic properties are designated as separate GWBUs.

Geoscience work performed in Step 1 should be conducted by a licensed professional geoscientist (P.G.) who is familiar with the recognition, delineation and organization of sediments from common depositional
systems. The resulting geoscience work products should be sealed by the
P.G. pursuant to 22 TAC §851.156.

2.3.5 Minimum Number of GWBUs at an Affected Property

The minimum number of GWBUs that are required to be reported at an
affected property are the following:

1. any delimited GWBUs into which a direct COC release has
   occurred, and

2. any interconnected GWBUs which potentially can be impacted by
   the affected GWBUs.

However, note that application of the rule in terms of setting assessment
levels, demonstrating sufficient assessment, development of PCLs,
defining PCLE zones and determining the appropriate response objectives
will be more complicated as the number of proposed GWBUs and
classifications increase. This is particularly true if multiple GWBUs and
groundwater classifications are laterally distributed across the affected
property. It may be more practical to assume the same higher-quality
classification (e.g., Class 2 is higher than Class 3) for all GWBUs at the
affected property.

2.4 STEP 2: Determine Hydraulic Interconnectivity of GWBUs

For purposes of groundwater classification, consider an affected GWBU to
be hydraulically interconnected with another GWBU if flow from one
GWBU may potentially cause an exceedence of a critical PCL in a
receiving GWBU. The evaluation of hydraulic interconnection must
consider the potential groundwater flow that can be induced between
separate hydrostratigraphic units as a result of pumping in the unaffected
unit. Such flow may occur as a result of 1) stratigraphic connections, 2)
the presence of artificial penetrations, or 3) leakage through intervening
confining layers. For the purpose of this evaluation, assume that the
groundwater production zone of the hypothetical pumping well is
screened only within the unaffected groundwater-bearing unit and is not
assumed to interconnect multiple strata. Where the hydraulic
interconnection is so pronounced that the two units hydraulically behave
as one, consider them one GWBU.

Table 6 summarizes some methodologies and example diagnostics that
can be applied to a line of evidence demonstration concerning the
determination of GWBU interconnectivity.

General lines of evidence that indicate the potential for hydraulic
interconnection of groundwater-bearing units, or the lack thereof, are
listed on Table 6. In many cases, evaluation of hydraulic interconnection
may be based upon a qualitative assessment of the type, thickness, and continuity of the intervening strata, in combination with evaluation of hydraulic head elevations and water quality data. If such data are inconclusive, the TCEQ may require additional field measurements to address potential interconnections, such as 1) *in-situ* hydraulic conductivity tests for intervening confining layers, 2) an aquifer pumping test within the unaffected groundwater-bearing unit to detect the presence or absence of a hydraulic response in the affected unit, or 3) other appropriate investigations.

The applicable groundwater resource classification for a given hydraulically-interconnected GWBU will be determined based upon consideration of the current use, water quality, and well yield of that individual GWBU only. Response objectives for affected GWBUs must serve to prevent impacts to hydraulically-interconnected unaffected GWBUs in excess of the applicable assessment levels for the unaffected GWBU.

**Table 6. Lines of Evidence for Hydraulic Interconnectivity of GWBUs**

<table>
<thead>
<tr>
<th>Type of Information</th>
<th>Example Line-of-Evidence Conditions for Use in Determining Hydraulic Interconnection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Not Interconnected</strong></td>
<td></td>
</tr>
<tr>
<td>1) Stratigraphic Data</td>
<td>• Homogeneous, unfractured, continuous clay stratum ≥ 20 ft in thickness.</td>
</tr>
<tr>
<td>Thickness, continuity, and hydrologic</td>
<td>• Confining unit is laterally discontinuous, highly fractured, or composed of</td>
</tr>
<tr>
<td>properties of intervening confining layer.</td>
<td>permeable material.</td>
</tr>
<tr>
<td>2) Static Water Levels (SWL)</td>
<td>• Significant SWL difference between wells screened above and wells screened below</td>
</tr>
<tr>
<td>Relative hydraulic head elevations in</td>
<td>confining unit.</td>
</tr>
<tr>
<td>separate GWBUs.</td>
<td>• SWLs are identical above and below confining unit.</td>
</tr>
<tr>
<td>3) Affected Groundwater</td>
<td></td>
</tr>
<tr>
<td>Presence or absence of affected groundwater</td>
<td>• Affected groundwater present in all GWBUs.</td>
</tr>
<tr>
<td>in GWBUs.</td>
<td></td>
</tr>
<tr>
<td>4) Natural Water Quality</td>
<td>• Separate GWBU is not affected and exhibits significantly different TDS and/or</td>
</tr>
<tr>
<td>Contrast in natural water quality</td>
<td>major ion distribution from affected unit.</td>
</tr>
<tr>
<td>characteristics (e.g., Total Dissolved</td>
<td></td>
</tr>
<tr>
<td>Solids (TDS), major ion distribution, etc.)</td>
<td></td>
</tr>
<tr>
<td>5) Field Hydraulic Conductivity Test</td>
<td>• Confining unit is laterally continuous with vertical hydraulic conductivity ≤ 10^{-7}</td>
</tr>
<tr>
<td>In-situ field hydraulic conductivity tests</td>
<td>cm/sec.</td>
</tr>
<tr>
<td>performed on intervening confining unit.</td>
<td>• Confining unit exhibits vertical hydraulic conductivity ≥ 10^{-5} cm/sec.</td>
</tr>
<tr>
<td>6) Aquifer Pumping Test</td>
<td>• No measurable SWL drop (e.g., &lt; 0.01 ft corrected for barometric variations)</td>
</tr>
<tr>
<td>Field test conducted to evaluate effect of</td>
<td>observed in affected unit within 24-hour period of continuous pumping from</td>
</tr>
<tr>
<td>pumping from unaffected unit on SWL in</td>
<td>unaffected unit.</td>
</tr>
<tr>
<td>affected unit.</td>
<td>• Measurable SWL drop observed in affected unit as a result of pumping in</td>
</tr>
<tr>
<td></td>
<td>unaffected unit.</td>
</tr>
</tbody>
</table>
2.5 STEP 3: Determine Current Groundwater Use

For the purpose of groundwater resource classification, the current use of affected GWBUs and any threatened, hydraulically-interconnected units must be characterized. The groundwater-use data support evaluation under §350.52(1)(A) and §350.52(2)(B). As specified in §350.51(i), characterization of current groundwater use will involve the following tasks:

1. **Records Survey**: Conduct a records survey to identify all water wells within a 0.5-mile distance of the limits of groundwater that contains COCs in excess of the residential assessment level (i.e., affected groundwater).

2. **Field Survey**: Conduct a field survey to identify any existing water wells located to at least 500-foot distance of the boundary of the affected property.

Current status and actual condition of wells that result from the above surveys should be determined. Note that the provision “existing well” in §350.52(1)(A) and §350.52(2)(A) means that as water supply wells are put into service or permanently abandoned in the vicinity of the affected property, the groundwater classification can adjust up or down during the life span of the remediation project.

2.5.1 Required Information Regarding Current Water Use

Documentation of the current use evaluation shall include:

1. a scale map showing water supply wells located within 0.5 miles of the affected groundwater, and

2. a complete tabulation of available information on a) well use, b) well construction (screened interval, seal, etc.), and c) groundwater production zone, as determined from available water well driller's logs, groundwater resource publications (e.g., Texas Water Development Board, United States Geological Survey, University of Texas Bureau of Economic Geology, etc.), and other relevant sources.

If documentation of water well construction/completion (i.e., drilling logs or other well construction records submitted to the State) is not available assume that the well is completed within the affected GWBU unless that well is inspected for completion construction details, well casing integrity
and potential for cross-communication. Additionally, if the well use is uncertain, presume the well is used as a drinking water source.

Identification of monitoring well locations is not the focus of the well surveys required for the groundwater resource classification. However, monitoring wells can provide valuable groundwater classification information (e.g., identify high TDS groundwater).

It is recommended that available groundwater resource publications be reviewed in order to 1) provide insight into and understanding of the subsurface, 2) identify the major groundwater production zones underlying the affected property, and 3) assess their potential interconnection with affected GWBU.

2.5.2 Applicable Groundwater Resource Classification

A preliminary groundwater resource classification can be determined in this step if any of the following groundwater resource conditions are identified during the groundwater use survey (see §350.52):

1. **Proximity to Public Water Supply Well:** Drinking water supply well serving public water system (as defined under 30 TAC §290.38) is located within 0.5 miles, and the groundwater production zone of this well potentially could be impacted by COCs from the affected GWBU. **Applicable Groundwater Resource Classification: Class 1.**

2. **Only Reliable Water Source Affected:** The affected GWBU is the only reliable source of drinking water (i.e., a connection to a public water system is not currently available and will not be provided to the affected property as part of the remedy) located within 800 feet below grade in the area, groundwater TDS < 1,000 mg/L, and well yield for 4-inch diameter well > 5,000 gpd. **Applicable Groundwater Resource Classification: Class 1.**

3. **Proximity to Other Water Supply Well:** Domestic (private) water supply well used for drinking water, agricultural supply, or other use (other than a public water supply) that could result in human or ecological exposure is located within 0.5 miles of the affected property and has groundwater production zone within the affected groundwater-bearing unit. **Applicable Groundwater Resource Classification: Class 2 (unless otherwise Class 1, based on consideration of well yield and natural water quality).**

If the results of this evaluation show the affected GWBU to qualify as a Class 1 groundwater resource (based on Conditions 1 or 2, as described above), no further evaluation of the resource classification is necessary. The person can proceed directly to Step 7: Documentation.
The following example explores the subtle distinction between §350.52(1)(A) and §350.52(2)(A) with regard to groundwater production zone. Figure 2 depicts the subsurface conditions for the example. Two GWBUs exist at the affected property. GWBU A is unconfined. GWBU B is confined and is the groundwater production zone for the well in the example. The affected groundwater is less than 0.5 miles from the well. In the example, four separate scenarios are evaluated for the purpose of illustrating how GWBU A should be classified under different conditions. In all of the scenarios, the well is sealed across GWBU A and there is no leakage down the well bore. In the scenarios, the classification of GWBU A is dependent upon whether the well is a public or domestic water supply well, the groundwater production zone, hydraulic interconnectivity between GWBUs A and B, COC transport properties, and the intrinsic characteristics of GWBU A.

1. **Scenario 1**: The well is a public water supply well and based on hydraulic interconnection between GWBUs A and B and the transport characteristics of the COCs, GWBU A will contribute COCs to the groundwater production zone (GWBU B) for the well.
   
   **GWBU A Classification**: Class 1 in accordance with §350.52(1)(A) since the affected groundwater (GWBU A) is within 0.5 miles of a public water supply well, and GWBU A will contribute COCs to the groundwater production zone (GWBU B) for the public water supply well.

2. **Scenario 2**: The well is a public water supply well and based on lack of hydraulic interconnection between GWBUs A and B and transport characteristics of the COCs, GWBU A will not contribute COCs to the groundwater production zone (GWBU B) for the well.
   
   **GWBU A Classification**: Class 1, 2, or 3 based on the characteristics of GWBU A. Although the affected groundwater (GWBU A) is within 0.5 miles of the public water supply well, GWBU A is not the groundwater production zone for the well and will not contribute COCs to the groundwater production zone. Therefore, §350.52(1)(A) is not applicable.

3. **Scenario 3**: The well is a domestic water supply well and based on hydraulic interconnection between GWBUs A and B and the transport characteristics of the COCs, GWBU A will contribute COCs to the groundwater production zone (GWBU B) for the well.
   
   **GWBU A Classification**: Class 1, 2 or 3 based on the characteristics of GWBU A. Because the well is not a public water supply well, §350.52(1)(A) is not applicable. Although the affected groundwater is within 0.5 miles of the domestic well, because GWBU A is not the groundwater production zone for the well, §350.52(2)(A) is not applicable. However, because GWBU A is contributing COCs to the groundwater production...
zone (GWBU B), the standard response objectives for the applicable classification for GWBU A may need to be modified so that the response objectives for GWBU B can be met.

4. **Scenario 4:** The well is a domestic water supply well and based on lack of hydraulic interconnection between GWBU A and B and transport characteristics of the COCs, GWBU A will not contribute COCs to the groundwater production zone (GWBU B) for the well.

**GWBU A Classification:** Class 1, 2 or 3 based on the characteristics of GWBU A.

---

![Figure 2: Hydrostratigraphic Scenario for Multiple GWBU Classification Example.](image)
Table 7 summarizes the conditions and classification results of the example scenarios.

<table>
<thead>
<tr>
<th>Production Zone</th>
<th>Well Type</th>
<th>GWBU A Contributes COCs to GWBU B</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>GWBU B</td>
<td>Public Supply Well</td>
<td>YES</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>GWBU B</td>
<td>Public Supply Well</td>
<td>NO</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>GWBU B</td>
<td>Domestic Supply Well</td>
<td>YES</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>GWBU B</td>
<td>Domestic Supply Well</td>
<td>NO</td>
</tr>
</tbody>
</table>

2.6 STEP 4: Evaluate Natural Groundwater Quality

For the purpose of groundwater resource classification, the natural (background, not anthropogenic) water quality of a groundwater-bearing unit is to be characterized on the basis of the background total dissolved solids (TDS) content of the groundwater.

2.6.1 Characterization of Natural Water Quality

To characterize natural TDS, groundwater should be collected properly from one or more background well locations in each affected GWBU (and any hydraulically-interconnected GWBU) and submitted for laboratory analysis of TDS content using EPA Method 160.2. All groundwater sample collection, preservation and handling procedures must conform to applicable TCEQ and United States Environmental Protection Agency guidelines. Composite groundwater samples are not acceptable for TDS analysis. Estimation of groundwater TDS based on measurement of specific conductance is not acceptable for the purpose of groundwater resource classification.

If groundwater samples are collected from multiple sampling locations within a single GWBU, the representative TDS value for that unit may be estimated as the arithmetic mean of the laboratory test results for the individual samples.
In some instances, an affected property may coincide with a TDS boundary or a transition between two different groundwater classifications within the same GWBU. Before “averaging” across the two different water quality zones, the person may opt to subdivide a commensurate portion of the GWBU into a lower-quality zone based on a higher TDS content per §350.52. Otherwise, the person can opt to demonstrate that there is not a portion of the affected property where the higher-quality water would not be degraded by drawing in the lower-quality water during pumping. If there are isolated high-TDS zones, then averaging the higher TDS water in this zone is not appropriate.

2.6.2 Applicable Resource Classification by Natural Groundwater Quality

The classification of groundwater resources based on the measured TDS content of the groundwater not meeting Class 1 or Class 2 in Step 3 (as summarized in Table 1 and Figure 1) follows:

1. **Representative TDS > 10,000 mg/L:** AND the GWBU does not qualify as Class 1 or 2 based on current groundwater use (see Step 3). **Applicable groundwater resource classification:** Class 3.

2. **Representative TDS ≤ 10,000 mg/L and > 3,000 mg/L:** AND the GWBU does not qualify as Class 1 based on current groundwater use (see Step 3). **Applicable groundwater resource classification:** Either Class 2 or Class 3, depending on well yield.

3. **Representative TDS ≤ 3,000 mg/L:** **Applicable groundwater resource classification:** Either Class 1, Class 2, or Class 3, depending on use and/or well yield.

If the results of the TDS evaluation show that the affected GWBU qualifies as a Class 3 groundwater resource based on TDS > 10,000 mg/L, no further evaluation of the resource classification is necessary. The person can proceed directly to Step 7: Documentation.

2.7 STEP 5: Evaluate Groundwater Resource Productivity

Aquifer parameters of GWBUs and well yield determinations must be estimated or directly measured from relevant GWBUs using appropriate protocols and methods. Discussion and methodologies that support the activities related to determining groundwater resource productivity include the following:

1. Monitoring/test well installation, development, and/or rehabilitation; and

2. Determination of hydraulic conductivity using single-well tests, multiple-well tests, or direct yield measurements.
Table 8 summarizes the purpose, applicability, requirements, and some caveats associated with the hydraulic test methods described herein.

<table>
<thead>
<tr>
<th>Method</th>
<th>Section</th>
<th>Purpose</th>
<th>Applicability</th>
<th>Requirements</th>
<th>Caveats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method 1</td>
<td>Section 2.7.1</td>
<td>Estimate of well yield by known $K$ and $b$ via calculations or well yield graphs</td>
<td>High to low GWBU transmissivities</td>
<td>Site-specific $K$ and $b$ (Attachment A)</td>
<td>Direct measurement method required if within 20% of GW class boundary</td>
</tr>
<tr>
<td>Method 2a</td>
<td>Section 2.7.2.2</td>
<td>Direct determination of well yield by cyclic discharge</td>
<td>High to low GWBU transmissivities</td>
<td>Measure total volume withdrawn and time to recharge</td>
<td>Minimum of three (3) cycles; Recharge cannot exceed 90%</td>
</tr>
<tr>
<td>Method 2b</td>
<td>Section 2.7.2.3</td>
<td>Direct determination of well yield by equilibrium discharge</td>
<td>Low GWBU transmissivities</td>
<td>Constant discharge rate (pumped or bailed)</td>
<td>Wells should not be pumped dry</td>
</tr>
<tr>
<td>Method 2C</td>
<td>Section 2.7.2.4</td>
<td>Direct determination of Class 2/Class 3 yield boundary by constant discharge</td>
<td>Low GWBU transmissivities</td>
<td>Constant discharge rate (0.1 gpm)</td>
<td>Discharge rate and water level should be monitored continuously</td>
</tr>
</tbody>
</table>

Figure 3 provides a decision tree to assist the person in the selection of the appropriate productivity method. Figure 3 shows a general framework to aid in selecting appropriate hydraulic testing and a guide to choices inherent in the use of the productivity methods.

Aquifer parameter and well yield determinations should be performed only after the following caveats have been addressed:

1. The person should be thoroughly familiar with all standard methods employed in the construction and development of test wells, implementation of test procedures, and reduction of test data. (See Attachment A.)

2. Test wells should be constructed in accordance with 16 TAC §§76.1000 – 76.1009. Additional guidance on appropriate test well depths, placement, development, and rehabilitation (if necessary) can be found in standard methods presented in Table A1 (Attachment A). It is strongly recommended that the use of non-standard methods be pre-approved by the TCEQ.

3. Guidance for multi-well test, single-well test and well yield determination procedures, data collection methods, and data reduction can be found in standard methods summarized in Tables A2, A3 and A4 (Attachment A). It is strongly
recommended that deviations from the standard test methods be pre-approved by the TCEQ.

4. Aquifer parameter and well yield determinations should be completed in wells that are most likely to produce the greatest yields or optimum flow rates from the GWBU. Typically, evaluation of the lithologic descriptions for the well borings, evaluation of well design, construction, completion and development, and observation of relative recharge rates following purging preparations for sampling will provide sufficient basis to identify the wells that are most suitable for testing.

![Figure 3. Decision Tree for Guidance in Selecting Productivity Tests.](image)

### 2.7.1 METHOD 1: Groundwater Classification by Calculation and Yield Graphs

For each location evaluated within a GWBU, the well yield is estimated using the hydraulic conductivity, the saturated thickness (or the confining head, for confined units only) at that location, and the appropriate form of the Method 1 equation (i.e., Equations A or B for

#### Use of Confined Yield Graph.

Figure 4 (for confined units) is based on a default confining head \((hc)\) of 10 feet. To use the graph, multiply the saturated thickness value \((b)\) at the site by a correction factor equal to the actual site-specific confining head \((hc)\) in feet and divide by 10 feet. Then define and plot the \((K, b)\) point for the representative hydraulic conductivity and the adjusted saturated thickness value.
confined units and Equations C or D for unconfined units in Figure 4). For use in evaluation of the Class 3 yield boundary (150 gpd), the default well radius in Equations A and C is set to 2 inches (4-inch diameter well screen). For use in evaluation of the Class 1 yield boundary, Equations B and D assume a default 6-inch well radius (12-inch diameter well screen).

Figure 4 summarizes the Method 1 well yield equations. For convenience, the Q = 150 gpd and the Q = 144,000 gpd well yield curves (and their respective ± 20% envelopes) are plotted on Figure 5 (for confined groundwater) and Figure 6 (for unconfined groundwater).

![Figure 4. Method 1 Equations for Estimating Well Yield.](image)

To use Figures 5 and 6, find the intersection of the saturated thickness value (b) and the hydraulic conductivity value (K) to define a point on the plot. The location of this (K, b) point on the plot indicates whether the well yield (Q) at that location falls in the Low (Q < 150 gpd), Moderate (150 gpd ≤ Q < 144,000 gpd), or High (Q ≥ 144,000 gpd) yield range.

Derivation of the Method 1 equations and full-scale reproductions of Figures 5 and 6 (for use in plotting actual data) are provided in Attachment B of this guide.

**NOTE:** If a GWBU meets the criteria for more than one groundwater classification, then the GWBU shall be assigned the higher (quality) classification (§350.52).
Figure 5. Method 1 Estimate of Well Yield for Confined GWBUs.

Figure 6. Method 1 Estimate of Well Yield for Unconfined GWBUs.
2.7.2 METHOD 2: Direct Well Yield Determination

If the representative well yield (Q) estimated from Method 1 indicates that the well yield is within ±20% (shaded area around boundary curves) of the Class 1 or Class 3 yield boundaries (Figure 5 or 6) and the resource classification is not otherwise dictated by current use or water quality (per Steps 3 and 4), then a Method 2 direct determination of well yield is required to confirm the appropriate groundwater resource classification. The use of Method 2 determinations is required for the following two conditions:

1. **Fresh Water, Class 1 Yield Boundary:** GWBU contains fresh water (water meets PDWS and TDS \( \leq 3000 \) mg/L), and Method 1 well yield estimate (using Figure 4 Equations B or D, as appropriate) falls within ±20% of the Class 1 yield boundary (i.e., \( 115,200 \) gpd \( \leq Q \leq 172,800 \) gpd).

2. **Non-Brackish Water, Class 3 Yield Boundary:** GWBU has representative TDS content that is \( \leq 10,000 \) mg/L, and Method 1 well yield estimate (using Figure 4 Equations A or C, as appropriate) falls within ±20% of the Class 3 yield boundary (i.e., \( 120 \) gpd \( \leq Q \leq 180 \) gpd).

Method 2 is particularly useful for low transmissivity GWBUs and could be useful for high transmissivity units, but can generate high volumes of wastewater in the latter. Method 2 comprises three different techniques by which a direct measurement of well yield can be obtained from a test well completed within a GWBU. If more than one test well is employed in these field measurements, they must be: 1) constructed with similar specifications, 2) located such that they are testing only the same GWBU (see Section 2.3.4), and 3) representative of the flow rate of water the GWBU is capable of transmitting to that well. If more than one test well location is used to test a single GWBU, the representative well yield should be determined as the geometric mean of the individual well test results.

Results from field tests previously conducted at the affected property can be used to evaluate well yield if the well construction and test procedures used in the prior tests are documented to conform to Method 2 guidelines, as detailed above.

**NOTE:** If a GWBU meets the criteria for more than one groundwater classification, then the GWBU shall be assigned the higher (quality) classification (§350.52).
2.7.2.1 METHOD 2: Discharge Methods.

The discharge method (e.g., hand bailing, suction pump, submersible pump, etc.) used in the yield test must be selected to meet the requirements of the test procedure and ensure that the measured well yield is not “pump-limited”. In all cases, the pump curve should show that the pump has sufficient power to produce water at the desired test flow rate, under the applicable suction intake and discharge pressure. The water intake point for the pump (i.e., pump intake for submersible pumps, suction hose for suction pumps, etc.) should be positioned below the lowest depth to water anticipated for the test.

Withdrawal in Method 2.
Suction pumps (such as centrifugal pumps, jet pumps, or peristaltic pumps) are typically limited to a practical suction-lift capacity of 25 feet below the pump intake, and may result in reduced discharge if the pumping water level falls below this depth during the test. In low-yield units, hand-bailing methods may be sufficient to evacuate the well, so long as bail-out speed does not cause limitations to test.

2.7.2.2 METHOD 2a: Well Yield by Cyclic Discharge.

Primarily used to test the Class 2/Class 3 150 gpd yield boundary in relatively low-yield GWBUs (defined as hydrostratigraphic units whose hydraulic conductivity can not be practically measured using the techniques described in Attachment A).

Method 2a comprises a cyclic bail down – recovery test. Method 2a is performed using the following procedure:

1. **Well Construction:** Test well must be fully-penetrating, have a minimum diameter of 2 inches, and be completed with construction details consistent with requirements of 16 TAC §§76.1000 - 76.1009.

2. **Initial Water Level:** Measure static water level in well.

3. **Water-Level Bail-Down:** Use bailer, pump, or other device to effectively evacuate all water from the well. Contain all discharged water and measure total volume ($V_1$). Measure static water level in well immediately upon completion of water removal.

4. **Time for Water-Level Recovery:** Monitor static water level in well and measure elapsed time ($t_1$) from completion of water removal until static water level in well recovers to the same specified level, up to, but not greater than 90% of height to initial static water level.

5. **Repeat Bail-Down and Recovery:** Repeat Steps 2 and 3 above twice. *This procedure requires a minimum of three bail-
**down/recovery cycles.** Record total volume of water \((V_1 \ldots V_n)\) removed from well during each successive bail-down and the elapsed time \((t_1 \ldots t_n)\) from completion of water removal until water level in well recovers to the same specified level used in prior cycle(s) (i.e., up to, but not greater than 90% of height to initial static water level).

The maximum well yield corresponds to the total bailed water volume \((\sum V_n)\) divided by the combined recovery time \((\sum t_n)\) measured during at least three bail-down/recovery cycles (see Equation 1).

\[
\text{Well Yield} = \frac{\sum_{i=1}^{n} V_i}{\sum_{i=1}^{n} t_i} \quad [\text{EQ 1}]
\]

Figure 7 provides an example of a bail-down test calculation performed for a well with approximately 3 feet of available drawdown. In such case, the well yield should be calculated as the total bailed water volume divided by the cumulative recovery time for all cycles and presented in units of **gallons per day** (gpd).

**Figure 7. Example of Cyclic Bail-Down and Recovery Well Yield Test**

### 2.7.2.3 METHOD 2b: Well Yield by Equilibrium Water Level Test.

To determine if a test well is capable of producing a yield of 150 gpd, the well may be pumped continuously at a discharge rate equivalent to well
recharge rate (well yield). In this Method, the well is pumped at a rate such that the pumping water level is maintained as near as practical to the base of the well screen. Test procedures are as follows:

1. **Well Construction:** Test well must be fully-penetrating, be a minimum diameter of 2 inches, and be completed with construction details consistent with requirements of 16 TAC §§76.1000 - 76.1009.

2. **Initial Water Level:** Measure static water level in well.

3. **Pump Installation:** Equip well with pump capable of maintaining a constant drawdown elevation near bottom of well.

4. **Water Level Equilibrium:** After pump and hose installation, monitor static water level in well until water has re-equilibrated to initial water level.

5. **Well Pumping:** Activate pump and set discharge rate to achieve a pumping water level as near as practicable to the base of well screen. Adjust pump discharge rate until it is equivalent to well recharge rate (i.e., water level near the bottom of well remains constant and is lower than static water level).

6. **Measure Equilibrium Discharge Rate:** Once the new water-level equilibrium has been established in the test the pump discharge rate is determined. The pump discharge rate is then converted to units of gallons per day (gpd). Test is complete when a total water volume of 50 gallons has been produced or pumping has been underway for 8 hours, whichever comes first.

7. **(Optional:** The person may choose to perform the test for a longer period of time. There is no limit on the maximum length of the test period. However, if the test period extends beyond 24 hours, bear in mind the results need to be evaluated and conclusions must be presented in a manner consistent with the per day yield criteria of the rule.)

### 2.7.2.4 METHOD 2c: Well Yield by Constant Discharge (0.1 gpm) Test.

To determine if a test well is capable of producing a yield of 150 gpd, the well may be pumped continuously at a discharge rate equivalent to 0.1 gallons per minute (gpm), or 150 gpd. In this Method, the well is pumped as near as practicable to the base of the well screen at a rate equal to 0.1 gpm. If the well’s water level does not fall to the pump inlet level during the test, the well is considered capable of producing a minimum yield of 150 gpd. Test procedures are as follows:

1. **Well Construction:** Test well must be **fully-penetrating**, have a minimum diameter of 2 inches, and be completed with
construction details consistent with requirements of 16 TAC §§76.1001-76.1005.

2. **Initial Water Level:** Measure static water level in well.

3. **Pump Installation:** Equip well with pump capable of maintaining a constant discharge rate of 0.1 gpm and a pump inlet placement near bottom of well.

4. **Water Level Equilibrium:** If the test well water level remains constant during test, or if the test well water level falls to a new static equilibrium water level elevation, the well yield is 150 gpd or greater.

5. **Well Pumping:** The pumping should be monitored continuously and the discharge rate corrected for deviations due to changes in hydrostatic pressure when test well water level falls.

6. **Test Termination:** Test is complete when a total water volume of 150 gallons has been produced, when test well water level falls to bottom of well (no re-equilibrium), or when test duration reaches 8 hours, whichever comes first. The ability to maintain the 0.1 gpd discharge rate indicates Class 2 well yield. The results should be converted to a volume discharged per 24 hour (gpd).

7. **(Optional:** The person may choose to perform the test for a longer period of time. There is no limit on the maximum length of the test period. However, if the test period extends beyond 24 hours, bear in mind the results need to be evaluated and conclusions must be presented in a manner consistent with the per day yield criteria of the rule.)

---

**2.7.3 Saturated Soil**

Zones of saturation with bulk hydraulic conductivities, \( K < 1 \times 10^{-5} \text{ cm/sec} \) are not classified or regulated as GWBU. Rather, such zones are regulated as saturated soils.

Demonstrations intended to show that certain saturated geologic strata are *not* GWBUs should be based on the following minimum supporting documentation (*see also* Table 5 for additional requirements):

1. data requirements for Class 3 demonstrations (Sec 1.4.3),

2. field measurements showing a representative hydraulic conductivity, \( K < 1 \times 10^{-5} \text{ cm/sec} \) (required); and

3. laboratory USCS classification as a clay or silty clay soil stratum (i.e., CH or CL), as confirmed by laboratory testing.

All water-saturated strata or groups of water-saturated strata that are shown not to meet one or more of the exclusion criteria listed below will
be assumed to be GWBUs for the purpose of the affected property assessment.

2.7.3.1 Direct Measurement of Hydraulic Conductivity.

To demonstrate that a water-saturated stratum is only a low hydraulic conductivity saturated soil, the person conducting the affected property assessment must obtain a site-specific measurement of hydraulic conductivity, usually by a single-well (slug) test, as described in Section A.3 (Attachment A) of this document. Hydraulic conductivity estimates based on laboratory permeability tests or soil grain-size analyses are not acceptable for the purpose of classifying a hydrostratigraphic unit as a saturated soil. Test wells used for purposes of measuring hydraulic conductivity must be properly constructed and developed so as to provide an accurate indication of the hydraulic properties of the stratum (see Section A.2; Attachment A).

When the saturated unit has a hydraulic conductivity that is too low to test effectively (e.g., no recharge observed during a test period of appropriate length), then an assumption that the hydraulic conductivity is less than $1 \times 10^{-5}$ cm/sec may be appropriate, provided the person can provide a sound and reasoned justification that the inability to effectively test the unit is reflective of the characteristics of the saturated unit and not the design, construction or development of the test well (e.g., insufficient well screen, partial penetration, skin effects, etc.). The reasoned justification should include the USCS soil classification referenced in Section 2.7.3.

2.7.3.2 USCS Soil Classification.

Laboratory confirmation, by ASTM Standard Practice D2487, of a CL or CH designation for a homogenous clay stratum is recommended to corroborate the low hydraulic conductivity measurement.

2.7.3.3 Interbedded Soils.

A clay stratum (i.e., CL or CH) containing water-saturated sand or silt seams or partings is classifiable as a GWBU if the measurable bulk lateral hydraulic conductivity of the stratum is $K \geq 1 \times 10^{-5}$ cm/sec. In the instance of the presence of interbedded seams or partings within a clay stratum, additional information will be required to confirm the appropriate
hydrologic characterization of the stratum. For example, a more detailed analysis of the stratigraphic profile may be necessary. Field measurements of bulk hydraulic conductivity of small intervals of the greater stratigraphic column may be required to demonstrate that the stratum’s effective K is less than $1 \times 10^{-5}$ cm/sec.

2.7.3.4 Confirmation by COC Transport.

A confirmation check should be applied based on the observed patterns of COC migration in the subsurface. If the lateral extent of COCs within the stratum is indicative of an effective $K \geq 1 \times 10^{-5}$ cm/sec (i.e., groundwater or the COC plume has traveled a lateral distance within the stratum from the source with a travel time that indicates an effective $K \geq 1 \times 10^{-5}$ cm/sec), then the discrepancy must be resolved and a higher burden of proof may apply to verify that the stratum is not a GWBU. See TCEQ guidance document Affected Property Assessment Requirements (RG-366/TRRP-12) for requirements for assessment of COCs in such low permeability saturated soils.

2.8 STEP 6: Evaluate Groundwater Resource Sustainability

An important aspect of discriminating between Class 2 and Class 3 groundwater resources is the ability for that resource to produce useable water at a sustainable rate of 150 gallons per day ... [§350.52(3)]. The capability of a groundwater resource to maintain an annualized sustainable daily withdrawal rate of 150 gpd is the basis by which a GWBU is classified in this step. Sustainability is also a consideration for Class 1 groundwater resources, but since most classification efforts are focused on distinguishing Class 2 and 3 groundwater resources, sustainability guidance here emphasizes distinguishing the Class 2/Class 3-classification boundary.

All well yield determinations are considered to be representative of a sustainable resource. However, in lieu of a short-term hydraulic test that can predict the consequence of long-term sustained withdrawal of water of useable quality from a groundwater resource, alternate methods can be applied to demonstrations that a GWBU does not meet the “sustainable” qualification. These non-hydraulic methods include:

- Ephemeral saturation, and/or
- Limited hydrogeologic extent

Demonstrations can be based on relevant characteristics of the unit. Such demonstrations require rigorous analysis and can include characteristics
such as geologic extent, ephemeral saturation, etc., and combinations thereof. Content of these demonstrations are described below:

2.8.1 Ephemeral Saturation

GWBUs that can be demonstrated to be: 1) historically ephemeral (not persistently saturated) and 2) hydraulically isolated from other GWBUs such that they do not produce sustainable yields may be downgraded to Class 3. Demonstrations must be based on documented historical water level observations or other unequivocal information that permits a conclusion that the GWBU is not permanently saturated, or otherwise is predictably ephemeral.

If a GWBU is historically or predictably dry on a seasonal basis, then it meets the criterion for classification as Class 3 unless there is a current use of the GWBU. Such examples can include groundwater accumulations within a perched GWBU, underlain by unsaturated soils, and which diminishes during dry weather periods. If the GWBU goes completely dry at any time during the year, such that no water can be collected within a fully-penetrating monitoring well, then a Class 3 groundwater resource classification applies to the GWBU. The TCEQ may require documentation in the form of periodic water-level monitoring for a minimum of one year to support the classification.

2.8.2 Limited Hydrogeologic Extent

Certain GWBUs may be demonstrated to be insufficiently extensive laterally and/or volumetrically and/or to be hydraulically isolated from other GWBUs and other sources of recharge such that the GWBU can not sustain the required long-term daily withdrawal rate to be a Class 1 or a Class 2 groundwater resource. Demonstrations of limited hydrogeologic extent must be based on both site-specific and regional hydrogeology, including detailed hydrostratigraphic analysis. Hydrogeological analysis of a sedimentary GWBU should include placement of the hydrostratigraphic unit within its overall stratigraphic context. The geometry of the hydrostratigraphic unit must be determined on a site-specific basis and the demonstration must rely on the limited extent of that geometry.

Examples of qualifying hydrostratigraphic units include lobes of permeable alluvial fans isolated by intercalated impermeable units, perched groundwater zones, and other isolated zones of saturation that are not used as groundwater resources.
2.8.3 Additional Lines of Evidence for Non-Sustainability Demonstration

Demonstrations to show that a groundwater resource is non-sustainable by ephemeral saturation and/or limited hydrogeologic extent may be strengthened using supplemental information from regional aquifer studies, groundwater resource assessments, water budget analyses, groundwater-surface water interactions, saline water intrusion studies, etc.

2.8.4 Classification of Karst or Fractured Groundwater-Bearing Units

A karst (or karstic) GWBU is defined here as a hydrostratigraphic unit composed primarily of soluble carbonate rock (such as limestone or dolomite) in which water flows appreciably through joints, fractures, faults, bedding-plane partings and/or cavities, any of which have been enlarged by dissolution.

A fractured GWBU is defined here as a hydrostratigraphic unit that exhibits breaks, whether or not caused by displacement, resulting from mechanical failure due to stress and includes cracks, joints, faults and other mechanical discontinuities, and groundwater movement is principally limited to the fractures.

In situations where the karstic or fractured character of a GWBU is the primary control on groundwater flow such that porous media flow is not the dominant character of the GWBU, then all aquifer parameter measurements (e.g., transmissivity) and calculations must be conducted by methods specifically appropriate to usage in karst or fractured GWBUs, as applicable. However, the direct well yield test methods presented in this guide should be generally applicable provided the test wells are designed and located such that their measurements are representative of the karst or fracture network when karst or fractures are expected to be the principal control on groundwater flow. See Table A4 (Attachment A) for more specialized methods for karst and fractured GWBUs. Also, bear in mind that a GWBU can be so intensely fractured or karsted such that it can mimic porous media flow. Therefore, unless it is clear that porous media flow is not reflective of the GWBU because of its karst or fracture character, the standard tests described in this document can be used.
2.9 STEP 7: Document Results

The results of the groundwater resource classification for all affected GWBUs and threatened hydraulically-interconnected GWBUs shall be submitted for TCEQ review in Section 2.5 of the Affected Property Assessment Report (APAR). The report should provide sufficient explanation and documentation to demonstrate proper classification of the groundwater resource and support TCEQ review. The responsibility is on the person to methodically present a convincing justification that the groundwater is Class 2 or Class 3. Applicable documentation includes the following:

Early Approval of Classification.

The person is encouraged to submit to the TCEQ groundwater information used to support a Class 3 classification prior to full completion and submittal of the APAR. Submit information on applicable APAR worksheets and attachments. In some instances, ensuring early TCEQ concurrence with a Class 3 groundwater classification can eliminate delays and remobilizations for additional assessment, revision of portions of the APAR, and duplication of work.

NOTE: All geoscience work submitted must be sealed by a licensed P.G. (per 22 TAC §851.156).

2.9.1 Identification of Groundwater-Bearing Units

Describe stratigraphic conditions, including geologic cross-sections and field and laboratory soil classification results, and provide supporting data related to identification of GWBUs, including soil type, water saturation, and applicable hydraulic conductivity. Evaluate potential hydraulic interconnection of affected GWBUs with other unaffected units.

2.9.2 Current Use and General Hydrogeologic Context

Provide a scaled map showing water supply wells located within 0.5 mile of the affected groundwater area; a tabulation of available information regarding any and all well use; and well construction (screened interval, seal, etc.), and the groundwater production zone as determined from available water well driller’s logs, groundwater resource publications, and other relevant sources. Identify principal groundwater production zones for any identified wells.

2.9.3 Aquifer Testing

For Method 1, identify the applicable Method 1 equation (confined or unconfined, 4-inch or 12-inch diameter well) and selected calculation locations, and for each location, justify site-specific calculation inputs, including saturated thickness, mean annual confining head (if applicable), and hydraulic conductivity (i.e., results of soil classification tests, rising head slug tests, constant-rate pumping tests, etc.).
For Method 2 well yield measurements, provide information on test well location(s) including the reasoning for selecting those test locations, test well construction and development, test procedures, all field data, the calculations used to reduce the data, the results of each calculation, and waste management procedures. Document all calculations of representative well yield for unit.

2.9.4 Natural Water Quality

Provide results of laboratory TDS analyses, including background sampling locations and the basis for assuming they represent natural background TDS, sample collection and handling procedures, and relevant quality assurance/quality control information. Provide information regarding compliance with PDWS criteria, if evaluated.

2.9.5 Groundwater Resource Sustainability

In the circumstance that a GWBU can be demonstrated to be a unit incapable of meeting the sustainability criterion, provide a hydrogeological analysis based on hydrostratigraphy, history of ephemeral saturation, observed ephemeral saturation, or any other site-specific hydrogeologic aspect sufficient to support the contention for a sustainability exemption.

2.9.6 Groundwater Resource Classification

Based on the results of the evaluation, identify the applicable classification in Section 2.5 of the APAR.

NOTE: If a GWBU meets the criteria for more than one groundwater classification, then the GWBU shall be assigned the higher (quality) classification (§350.52).
ATTACHMENT A

Determination of Hydraulic Conductivity in Groundwater-Bearing Units

The determination of hydraulic conductivity in GWBUs may be performed using either multiple-well or single-well methods. Tables A1 through A4 summarize the guidelines useful for determining what drilling and testing methods may be the best for specific site conditions. Acceptable methods are not limited to ASTM methods.

NOTE: If a GWBU meets the criteria for more than one groundwater classification, then the GWBU shall be assigned the higher (quality) classification (§350.52).

A.1 Monitoring/Test Well Installation, Development and Rehabilitation

Monitoring wells employed for measurement of hydraulic properties must be screened within the GWBU under investigation and must be designed, constructed, and developed in accordance with 16 TAC §§76.1000-76.1009. For convenience, additional guidance on recommended methods for the design, construction and installation of monitoring/test wells can be found in Tables A1 and A4.

Wells used for test purposes should be of conventional construction with a minimum nominal 2-inch diameter (push probes, etc. are not acceptable). Some recommended methods for the conventional advancement of borings and drilling methods for geoenvironmental investigations are listed in Table A1.

The Class 3 well yield limit (150 gpd) is based on a well with a nominal 4-inch diameter well screen or the equivalent. The Class 1 yield limit (144,000 gpd) is based on a well with a nominal 12-inch diameter well screen or the equivalent. If a well with a screen diameter other than 4-inch or 12-inch is used for the yield test(s), the equivalent yield from a 4-inch or 12-inch diameter well can be determined by multiplying the measured yield by the correction factors provided in Attachment C.

Well Construction. Test results from wells that are not appropriately designed, constructed, and/or developed may not be acceptable for groundwater classification purposes.

Prior to Well Installation. It is beneficial to obtain hydro-geologic information of the area in order to advance borings and select proper well construction specifications for future hydraulic testing.
A.2 Determination of Hydraulic Conductivity using Multiple-Well Tests

Site-specific values for hydraulic conductivity of GWBUs can be determined by multiple-well aquifer pumping tests conducted on wells screened within the GWBU. Control wells and observation wells used for this purpose must be constructed and developed in accordance with Section 2.7. The general procedure for a constant-rate pumping test involves:

1. selection of a well array consisting of one control well and two or more observation wells located at various distances from the control well;
2. measurement of initial static water levels in all wells to be used in the test;
3. discharge of groundwater from the control well at a known flow rate for the time period necessary to meet test requirements (i.e., until sufficient time-drawdown or distance-drawdown data are obtained, typically 2 to 24 hours); and
4. measurement of recorded water levels at appropriate time intervals in all test wells during both the period of pumping and during the period of water level rebound after cessation of pumping.

Multiple-well pumping tests provide an estimate of the transmissivity (T), storativity (S) and hydraulic conductivity (K) of the GWBU over the area influenced by the test. A pumping test performed on a GWBU that is not laterally extensive requires a modified test method. Additional guidance on testing areally-bound GWBUs, such as GWBU with limited lateral extent (e.g., fluvial channels) can be found in ASTM Test Method D 5270.

Methods for selecting multiple-well pumping tests appropriate to site conditions should be conducted in accordance with ASTM Standard Guide D 4043. Procedures for conducting multiple-well pumping tests in unconfined GWBUs are contained in ASTM Test Method D 5920. Procedures for conducting multiple-well pumping tests in extensive confined GWBUs are provided in ASTM Test Methods D 4106, D 5472, D 5473, and D 5850. Procedures for conducting multiple-well pumping tests in areally-bounded confined GWBUs can be found in ASTM Test Method D 5270. Table A2 summarizes various recommended standard methods applicable to multiple-well tests.
Table A-1. Recommended Methods for Drilling/Installing GWBU Monitoring/Test Wells

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Application</th>
<th>Recommended Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable-tool drilling, &amp; soil sampling</td>
<td>Geoenvironmental drilling and well installation</td>
<td>ASTM Guide D 5875</td>
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<tr>
<td>Auger boring for soil investigation</td>
<td>Auger drilling</td>
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<tr>
<td>Hollow-stem auger, soil sampling</td>
<td>Hollow-stem auger drilling</td>
<td>ASTM Practice D 6151</td>
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<tr>
<td>Air-rotary drilling, installation of monitoring wells</td>
<td>Geoenvironmental drilling and well installation</td>
<td>ASTM Guide D 5782</td>
</tr>
<tr>
<td>Direct rotary drilling, casing, soil sampling</td>
<td>Geoenvironmental drilling and well installation</td>
<td>ASTM Guide D 5876</td>
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<tr>
<td>Direct rotary drilling w/ water-based drilling fluid</td>
<td>Geoenvironmental drilling and well installation</td>
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</tr>
<tr>
<td>Dual-wall reverse-circulation drilling, installation of monitoring wells</td>
<td>Geoenvironmental drilling and well installation</td>
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<tr>
<td>Casing advancement for monitoring well installation</td>
<td>Geoenvironmental drilling and well installation</td>
<td>ASTM Guide D 5872</td>
</tr>
<tr>
<td>Casing advancement for monitoring well installation (wireline)</td>
<td>Geoenvironmental drilling and well installation</td>
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<td>Soil sampling in vadose zone</td>
<td>Geoenvironmental sampling</td>
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<td>Split-barrel sampling of soil</td>
<td>Geoenvironmental sampling</td>
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<td>Thin-walled tube sampling of soil</td>
<td>Geoenvironmental sampling</td>
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<td>Well development</td>
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<td>Monitoring well protection</td>
<td>ASTM Practice D 5787</td>
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<tr>
<td>Monitoring well installation in karst and fractured-rock aquifers</td>
<td>Well installation in karst and fractured rock</td>
<td>ASTM Guide D 5717</td>
</tr>
</tbody>
</table>

¹ Multiple procedures may be applicable at any one affected property.
The *representative transmissivity* value for a GWBU, appropriately determined, may be calculated as the arithmetic average of the transmissivity values determined for the various monitoring points used in the test (i.e., control well and observation wells). The representative transmissivity value may then be converted to a *representative* hydraulic conductivity (K) by dividing average T by the static saturated thickness (b) of the GWBU within the area of influence of the test, or:

$$K = \frac{T}{b}$$  \hspace{1cm} (A.1)

where:

- $K =$ representative hydraulic conductivity
- $T =$ representative transmissivity
- $b =$ aquifer thickness

Control well locations used for the purpose of averaging hydraulic parameters within a GWBU must be confirmed to insure that mean values are not biased low. The USGS (1979) provides additional information on multiple-well pumping tests.

### A.3 Determination of Hydraulic Conductivity using Single-Well Tests

Determination of site-specific hydraulic conductivity values may be determined using single-well tests. Slug tests (i.e., single-well *instantaneous discharge* head-change tests) must be conducted in wells that are constructed and developed in accordance with the provisions of 16 TAC §76.1000, the requirements in Section A.1 and the recommendations provided in Table A1.

**Instantaneous Discharge**

*Instantaneous discharge* in single-well tests requires withdrawal of water from a well sufficiently rapid such that no water is removed from storage (i.e., *gradual* withdrawal by pumping or multiple bailer-loads is not permitted).

*Special attention to well development efforts is required to ensure that drilling has not caused smearing of the borehole wall, or otherwise decreased the formation hydraulic conductivity, particularly when hollow- and solid-stem auger drilling methods are employed.*
Table A-2. Recommended Methods for Multiple-Well Aquifer Tests.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Method Use and Test Results</th>
<th>Test Applicability</th>
<th>Recommended Methods</th>
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</tr>
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<td>Field procedures for test wells</td>
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<td></td>
<td>ASTM Test D 4050</td>
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<tr>
<td>Controlling drawdown</td>
<td>Measure h, Q</td>
<td>Constant drawdown, variable discharge</td>
<td>ASTM Practice D 5786</td>
</tr>
<tr>
<td>Measuring water levels in observation wells</td>
<td>Measure h (in well)</td>
<td>Observation well</td>
<td>ASTM Test D 4750</td>
</tr>
<tr>
<td>Unconfined, anisotropic</td>
<td>Measure T, S, q, and $K_h/K_v$ ratio by Neuman Method</td>
<td>Constant discharge, &amp; fully- or partially-penetrating well</td>
<td>ASTM Test D 5920</td>
</tr>
<tr>
<td>Unconfined, radial-vertical anisotropy</td>
<td>Measure T, S, $K_h/K_v$</td>
<td>Drawdown $&lt;&lt; b$</td>
<td>ASTM Test D 5473</td>
</tr>
<tr>
<td>Unconfined, areally extensive</td>
<td>Measure T, specific capacity</td>
<td>Drawdown $&lt; 25% b$</td>
<td>ASTM Test D 5472</td>
</tr>
<tr>
<td>Unconfined, areally extensive</td>
<td>Measure T, S</td>
<td>Drawdown small vs $b$</td>
<td>ASTM Test D 4106</td>
</tr>
<tr>
<td>Unconfined</td>
<td>T by Recovery test</td>
<td>Drawdown small vs $b$</td>
<td>ASTM Test D 5269</td>
</tr>
<tr>
<td>Confined, non-leaky</td>
<td>Measure T, S</td>
<td>Fully-penetrating, constant discharge</td>
<td>ASTM Test D 4105</td>
</tr>
<tr>
<td>Confined, non-leaky</td>
<td>Measure T, S</td>
<td>Fully- or partially-penetrating, constant discharge</td>
<td>ASTM Test D 4106</td>
</tr>
<tr>
<td>Confined, non-leaky, bounded</td>
<td>Measure T, S for GWBU with limited areal extent</td>
<td>Confined unit with linear boundary</td>
<td>ASTM Test D 5270</td>
</tr>
<tr>
<td>Confined, radial-vertical anisotropy</td>
<td>Measure T, S, $K_h/K_v$</td>
<td>Minimum four (4) partially-penetrating wells</td>
<td>ASTM Test D 5850</td>
</tr>
<tr>
<td>Confined, non-leaky, radial-vertical anisotropy</td>
<td>Measure T, S, $K_h/K_v$</td>
<td>Partially-penetrating (vs fully penetrating)</td>
<td>ASTM Test D 5473</td>
</tr>
<tr>
<td>Confined</td>
<td>Measure T, specific capacity (well yield)</td>
<td>Fully penetrating, constant discharge</td>
<td>ASTM Test D 5472</td>
</tr>
<tr>
<td>Confined, non-leaky</td>
<td>T, by recovery test</td>
<td>Partially-penetrating</td>
<td>ASTM Test D 5269</td>
</tr>
</tbody>
</table>

$b$ - aquifer thickness  
$h$ – head  
$K$ - hydraulic conductivity  
$K_h$ – horizontal hydraulic conductivity  
$K_v$ – vertical hydraulic conductivity  
$Q$ – discharge rate  
$S$ - storativity  
$T$ - transmissivity  

Revised March 2010
If slug tests are performed to measure hydraulic conductivity for use in the Method 1 Calculation (see Section 2.7.1), the tests should be conducted at a minimum of three locations within each separate identified GWBU to provide a representative measure of the potential variability. Additionally, a minimum of three slug tests should be performed at each well to evaluate the possibility that “skin effects” are not dominating the results of the test. Butler et al. (1996) recommend using the same head displacement in the first and third test while using another head displacement for the second test.

The representative hydraulic conductivity value for a single GWBU is the geometric mean of the inter-well results from a single GWBU. The representative hydraulic conductivity value of a single well is the arithmetic mean of the intra-well results from that single well. The geometric mean of inter-well hydraulic conductivity is defined as:

\[ \bar{K} = \sqrt[n]{K_1 \cdot K_2 \cdot \ldots \cdot K_n} \]  
(A.2)

where,

\( \bar{K} \) = representative hydraulic conductivity
\( K_n \) = inter-well average hydraulic conductivity values
\( n \) = number of inter-well measurements

The general procedure for a single-well test involves:

1. measuring the initial static water level within the well to be tested;
2. inducing an instantaneous positive or negative change of water level; and
3. measuring the recovery towards static water level at appropriate time intervals.

**NOTE:** If a GWBU meets the criteria for more than one groundwater classification, then the GWBU shall be assigned the higher (quality) classification (§350.52).

Recommended field protocols, test procedures and data analysis methods for single-well tests are summarized on Table A-3.
### Table A- 3 Recommended Methods for Single-Well Tests.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Method Use and Test Results</th>
<th>Test Applicability</th>
<th>Recommended Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection of appropriate aquifer test</td>
<td>Single-well and multiple-well tests</td>
<td>Properly completed wells</td>
<td>ASTM Guide D 4043</td>
</tr>
<tr>
<td>Slugs for instantaneous discharge (head change)</td>
<td>Slug test</td>
<td>Properly completed wells</td>
<td>ASTM Test D 4044</td>
</tr>
<tr>
<td>Measuring water levels in observation wells</td>
<td>Slug test</td>
<td>Properly completed wells</td>
<td>ASTM Test D 4750</td>
</tr>
<tr>
<td>Unconfined</td>
<td>K</td>
<td>Instantaneous discharge</td>
<td>ASTM Test D 5912</td>
</tr>
<tr>
<td>Confined, non-leaky over-damped well response</td>
<td>T</td>
<td>Instantaneous discharge</td>
<td>ASTM Test D 4104</td>
</tr>
<tr>
<td>Confined, non-leaky under-damped well response</td>
<td>T</td>
<td>Instantaneous discharge</td>
<td>ASTM Test D 5785</td>
</tr>
<tr>
<td>Confined, non-leaky, critically-damped well response</td>
<td>T</td>
<td>Instantaneous discharge</td>
<td>ASTM Test D 5881</td>
</tr>
<tr>
<td>Constant head injection</td>
<td>T, S</td>
<td>Packers and pump</td>
<td>ASTM Test D 4630</td>
</tr>
<tr>
<td>Pressure pulse</td>
<td>T</td>
<td>Low transmissivity</td>
<td>ASTM Test D 4631</td>
</tr>
</tbody>
</table>

¹ Multiple procedures may be applicable at any one affected property.

K – hydraulic conductivity
S - storativity
T – transmissivity

### Table A- 4. Recommended Methods for Drilling and Monitoring Well Installation in Karst and Rock.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Method Use and Test Results</th>
<th>Test Applicability</th>
<th>Recommended Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection of appropriate aquifer test</td>
<td>Single-well and multiple-well tests</td>
<td>Properly completed wells</td>
<td>ASTM Guide D 4043</td>
</tr>
<tr>
<td>Rock core drilling and sampling</td>
<td>Geoenvironmental drilling and sampling of rock</td>
<td>Drilling method for rock</td>
<td>ASTM Practice D 2113</td>
</tr>
<tr>
<td>Monitoring well installation in karst and fractured-rock aquifers</td>
<td>Well installation in karst and fractured rock</td>
<td>Monitoring wells in karst/rock</td>
<td>ASTM Guide D 5717</td>
</tr>
</tbody>
</table>

¹ Multiple procedures may be applicable at any one affected property.

K – hydraulic conductivity
S - storativity
T – transmissivity
Figure 8. Confined Conditions

Note:

1) To use chart, align representative saturated thickness and hydraulic conductivity values to define (x,y) point on plot. Location of (x,y) point defines sustainable well yield category (low, moderate, or high). Note that this plot applies ONLY to confined units with confining head $h_c = 10$ ft. To match actual confining head, multiply saturated thickness ($b$) by ratio of (actual $h_c$ in ft) / (10 ft) before plotting (x,y) point. For example, if actual $h_c = 20$ ft, $b = 12$ ft, $K = 1.0E-3$, then correction ratio = 20 ft / 10 ft = 2. Plot point is $b = 2 \times 12 = 24$ ft; $K = 1.0E-3 \text{ cm/s}$. Yield = moderate (Class 2).

2) If a confined unit is expected to reach an unconfined condition during pumping (due to water level drawdown), the yield calculation should be based on the unconfined unit equation (see Figure 4).

3) If Method 1 yield estimate falls within +/- 20% of Class 1 or Class 3 yield boundary (gray zone), Method 2 direct well yield test required to confirm proper classification.

4) gpd = Gallons per day  Q = Well yield  K = Hydraulic conductivity (cm/sec)
GWBU = Groundwater-bearing unit  b = Saturated thickness (ft)  $h_c$ = Confining head (ft)

Legend
- Class 3 yield boundary ($Q = 150 \text{ gpd}$)
- Class 1 yield boundary ($Q = 144 \text{ K gpd}$)
- ± 20% zone
Figure 9. Unconfined Conditions

NOTES:

1) To use chart, align saturated thickness (b) and hydraulic conductivity (K) values to define (x,y) point on plot. Location of (x,y) point defines sustainable well yield category (low, moderate, or high). For example, if $K = 2 \times 10^{-3}$ cm/sec and $b = 10$ feet, then yield = moderate (Class 2).

2) If Method 1 yield estimate falls within +/- 20% of Class 1 or Class 3 yield boundary (grey zone), Method 2 direct well yield test required to confirm proper classification.

4) gpd = Gallons per day  
Q = Well yield  
b = Saturated thickness (ft)  
K = Hydraulic conductivity (cm/sec)

Legend:
- Class 3 yield boundary ($Q = 150$ gpd)  
- Class 1 yield boundary ($Q = 144$ K gpd)  
- + 20% zone
ATTACHMENT B

Method 1: Estimation of Well Yield Using Idealized Well Function Equation

Application of NonEquilibrium Well Function Equation

The Cooper and Jacob (1946) approximation to the Theis (1935) solution for radial groundwater flow to a pumping well is as follows:

\[
  s = \frac{2.3Q}{4\pi T} \left[ \log \left( \frac{2.25Tt}{r^2S} \times \frac{ft^3}{7.48\text{gal}} \right) \right]
\]  

(B.1)

where:

Q = rate of pumping (gallons per day)
T = transmissivity of water bearing unit (gpd/ft)
\( r \) = radial distance from well (ft)
S = coefficient of storage (dimensionless)
\( s \) = water level drawdown (ft) at pumping rate (Q) and distance (r)
\( t \) = time of pumping (days)

The equation is valid for large values of time (t) and/or small values of radial distance (r), such as will occur at a pumping well. For use in estimation of well yield, the equation may be simplified by incorporation of typical default values for less sensitive input parameters, as follows:

\( r \) = radius of well (2-inch for TRRP Class 3 yield limit, 6-inch for Class 1 yield limit)
S = \( 1.0 \times 10^{-4} \) (confined aquifer), \( 1.0 \times 10^{-1} \) (unconfined aquifer) (see Driscoll, 1986)
\( t \) = 7 days
T = \( K \times b \),
\[ K = \text{hydraulic conductivity (gpd/ft}^2\text{)} \text{ and} \]
\[ b = \text{saturated thickness of the unit in ft.} \]

Incorporating these default values, well yield Q may be expressed in terms of drawdown (s), hydraulic conductivity (K), and saturated thickness (b).
For a confined aquifer, 12-inch diameter well screen:

\[ Q = \frac{5.46(s)(K)(b)}{4.93 + \log(Kb)} \]  

(B.2a)

For a confined aquifer, 4-inch diameter well screen:

\[ Q = \frac{5.46(s)(K)(b)}{5.88 + \log(Kb)} \]  

(B.2b)

For an unconfined aquifer, 12-inch diameter well screen:

\[ Q = \frac{5.46(s)(K)(b)}{1.93 + \log(Kb)} \]  

(B.2c)

For an unconfined aquifer, 4-inch diameter well screen:

\[ Q = \frac{5.46(s)(K)(b)}{2.88 + \log(Kb)} \]  

(B.2d)

### Estimation of Well Yield Based on Hydrologic Parameters

The Cooper-Jacob equation may be used to calculate an estimate of well yield associated with a pumped water level drawdown \( s \) equal to the available drawdown in the well (i.e., the distance from the static water level to the lowest efficient pumping water level in the well).

In unconfined aquifers, a water level drawdown in excess of two-thirds of the saturated thickness does not significantly increase well yield. Consequently, design guidelines call for screening the lower one-half to one-third of the saturated unit, corresponding to an available drawdown \( s_{max} \) equal to 50% to 67% of the saturated thickness (Driscoll, 1986). However, wells completed in unconfined GWBUs that are used both for COC concentration monitoring and hydraulic testing should be fully penetrating.

In confined GWBUs, design guidelines call for screening the full saturated thickness of the aquifer, corresponding to an available drawdown equal to 100% of the confining head \( h_c \).

Based on these design guidelines, available drawdown may be expressed as:

- Confined unit: \( s_{max} = (1.0)(h_c)(e) \)
- Unconfined unit: \( s_{max} = (0.5)(b)(e) \)

where:

- \( h_c \) = confining head
- \( b \) = saturated thickness
- \( e \) = well efficiency
Substituting these available drawdown terms into the Cooper-Jacob expression (Equations 2a through 2d above), the well yield \( Q \) associated with utilization of the full available drawdown \( s_{\text{max}} \) can be calculated based on site-specific values of saturated thickness \( b \), hydraulic conductivity \( K \) and (for confined units) confining head \( h_c \), as follows:

**Confined Aquifer**

3a) 12-inch diameter well screen:

\[
Q = \frac{(115,846)(h_c)(K)(b)}{9.25 + \log[(K)(b)]} \quad \text{(B.3a)}
\]

3b) 4-inch diameter well screen:

\[
Q = \frac{(115,846)(h_c)(K)(b)}{10.2 + \log[(K)(b)]} \quad \text{(B.3b)}
\]

**Unconfined Aquifer**

3c) 12-inch diameter well screen:

\[
Q = \frac{(57,923)(K)(b^2)}{6.25 + \log[(K)(b)]} \quad \text{(B.3c)}
\]

3d) 4-inch diameter well screen:

\[
Q = \frac{(57,923)(K)(b^2)}{7.2 + \log[(K)(b)]} \quad \text{(B.3d)}
\]

where:

- \( b \) = saturated thickness of water-bearing unit (ft)
- \( h_c \) = confining head above top of water-bearing unit (ft)
- \( K \) = hydraulic conductivity of water-bearing unit (cm/s)
- \( Q \) = well yield (gpd)
- \( e \) = well efficiency (assumed to be 100%)

Note that, in each of the above expressions, well efficiency (which typically ranges from 70 to 80% in properly designed and developed wells) is assumed to be 100%, providing a theoretical upper-bound yield from an ideal well.
ATTACHMENT C

Estimation of Equivalent Method 2 Well Yield Based on Alternate Test Well Diameter

Overview of Method 2 Screen Diameter Correction Factors

For the purpose of the TRRP groundwater resource classification process, the person conducting the affected property assessment may estimate the yield from a properly constructed and developed well screened within the GWBU. Under the TRRP classification system, the Class 3 yield limit (150 gpd) is based on a well with a nominal 4-inch diameter well screen or the equivalent. The Class 1 yield limit (144,000 gpd) is based on a well with nominal 12-inch diameter well screen or the equivalent.

These specified well diameters have been incorporated in the Method 1 idealized well function equations presented in this guide (see Figures 4, 5, and 6 and Attachment A). No adjustment for well diameter is necessary or appropriate when using the Method 1 equations. However, under Method 2, any properly constructed and developed pumping well of nominal well screen diameter of 2 inches or greater may be used for the direct well yield tests. If a well with a screen diameter other than 4-inch or 12-inch is used for the yield test(s), the equivalent yield from a 4-inch or 12-inch diameter well can be determined by multiplying the measured Method 2 yield by the correction factors provided on Table C1. The derivation of the correction factors shown on Table C1 is provided below.

Application of Equilibrium Well Function Equation

The effect of the screen diameter on the well yield of a production well may be estimated using the equilibrium well function (Driscoll, 1986). The equilibrium well function equation (Thiem, 1906) relates well discharge to drawdown assuming two-dimensional radial flow toward the well as follows:

Unconfined Aquifer:

\[ Q = \frac{K(H^2 - h^2)}{1,055 \log \left( \frac{R}{r} \right)} \]  

(C.1a)
Confined Aquifer:

\[ Q = \frac{Kb(H - h)}{528 \log \left( \frac{R}{r} \right)} \]  

(C.1b)

where:

- \( Q \) = rate of pumping (gpm)
- \( K \) = hydraulic conductivity of groundwater-bearing unit (gpd/ft²)
- \( H \) = static head in well measured from base of the aquifer prior to pumping (ft)
- \( h \) = pumping head in well measured from base of the aquifer while pumping (ft)
- \( b \) = saturated thickness of the aquifer (ft)
- \( R \) = radius of the cone of depression (ft)
- \( r \) = radius of the well (ft)

Equations C.1a and C.1b are valid when all dynamic conditions in the well and groundwater are assumed to be in equilibrium (i.e., constant discharge, stable water level drawdown and radius of influence, and water flow converging on well at equal rates from all directions). The relationship of well yield to well screen diameter may be defined based on a simplified version of these equations, incorporating a constant term \( C \), as follows (Driscoll, 1986):

\[ Q \approx \frac{C}{\log \left( \frac{R}{r} \right)} \]  

(C.2)

For a 4-inch diameter well (Class 3) and a 12-inch diameter well (Class 1) in either an unconfined or confined aquifer, the well yield \( (Q) \) may be expressed in terms of the radius of the cone of depression \( (R) \), as follows:

12-inch diameter well screen

\[ Q = \frac{C}{\log \left( \frac{R}{0.5} \right)} \]  

(C.3a)

4-inch diameter well screen

\[ Q = \frac{C}{\log \left( \frac{R}{0.17} \right)} \]  

(C.3b)
Equations C.3a and C.3b can be used to calculate the equivalent yield from a 12-inch or 4-inch diameter well based on a measured yield from a well of a different diameter (e.g., 2-inch or 6-inch diameter well screen). For this purpose, the measured yield from the test well is multiplied by a correction factor equal to the ratio \( Q_{12\text{-in}}/Q_{\text{test}} \) for conversion to an equivalent flow from a well with a 12-inch diameter well screen or \( Q_{4\text{-in}}/Q_{\text{test}} \) for conversion to an equivalent flow from a well with a 4-inch diameter well screen.

For purpose of simplicity, the radius of the cone of depression (R) in Equation C.2 may be set equal to typical values for confined and unconfined groundwater-bearing units (i.e., 1,000 feet and 200 feet, respectively). Derivation of correction factors to estimate equivalent yields from wells with 12-inch or 4-inch diameter screens in either confined or unconfined units is shown below.

### Conversion Factors for Confined Unit

#### 12-inch Diameter Well Screen

**Correction**

\[
\frac{Q_{12\text{-in}}}{Q_{\text{test}}} = \frac{\log(R/r_{12\text{-in}})}{\log(1000/6)} = \frac{\log(1000) - \log(r_{\text{test}})}{3.3} \tag{C.4a}
\]

#### 4-inch Diameter Well Screen

**Correction**

\[
\frac{Q_{4\text{-in}}}{Q_{\text{test}}} = \frac{\log(R/r_{4\text{-in}})}{\log(1000/2)} = \frac{\log(1000) - \log(r_{\text{test}})}{3.8} \tag{C.4b}
\]

### Conversion Factors for Unconfined Unit

#### 12-inch Diameter Well Screen

**Correction**

\[
\frac{Q_{12\text{-in}}}{Q_{\text{test}}} = \frac{\log(R/r_{12\text{-in}})}{\log(200/0.5)} = \frac{\log(200) - \log(r_{\text{test}})}{2.6} \tag{C.5a}
\]

#### 4-inch Diameter Well Screen

**Correction**

\[
\frac{Q_{4\text{-in}}}{Q_{\text{test}}} = \frac{\log(R/r_{4\text{-in}})}{\log(200/0.17)} = \frac{\log(200) - \log(r_{\text{test}})}{3.1} \tag{C.5b}
\]
For above Equations C.4a through C.5b:

\[ r_{\text{test}} = \text{radius of wellscreen of test well (feet)} \]
\[ R = \text{radius of the cone of depression (feet)} \]
\[ Q = \text{well yield (gallons per day)} \]

Table C1 provides calculated conversion factors for a range of typical well screen diameters. For any given case, the appropriate conversion factor must be selected based upon: 1) the hydraulic condition of the groundwater-bearing unit (confined or unconfined), 2) the well screen diameter of the test well, and 3) the well screen diameter for which an equivalent yield is to be calculated (4-inch or 12-inch). The well yield determined from a Method 2 direct well yield test procedure \( Q_{\text{test}} \) is then multiplied by the appropriate correction factor to obtain the equivalent yield from a well with a 12-inch or 4-inch diameter well screen. This equivalent well yield is then used for determining the groundwater resource classification.

**Table C-1. Method 2 Correction Factors for Estimation of Equivalent Yield Based on Alternate Test Well Diameter**

<table>
<thead>
<tr>
<th>Nominal Screen Diameter of Test Well</th>
<th>Correction Factor for Equivalent Yield From:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4-inch Diameter Well</td>
</tr>
<tr>
<td></td>
<td>Confined Unit</td>
</tr>
<tr>
<td>2-inch</td>
<td>1.08</td>
</tr>
<tr>
<td>4-inch</td>
<td>1.00</td>
</tr>
<tr>
<td>6-inch</td>
<td>0.95</td>
</tr>
<tr>
<td>8-inch</td>
<td>0.92</td>
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<tr>
<td>10-inch</td>
<td>0.89</td>
</tr>
<tr>
<td>12-inch</td>
<td>0.87</td>
</tr>
<tr>
<td>16-inch</td>
<td>0.84</td>
</tr>
<tr>
<td>24-inch</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Multiply well yield measured in test well by the specified correction factor to obtain the equivalent yield of a well with either a 4-inch diameter screen or a 12-inch diameter screen.

**Example Calculation of Equivalent Well Yield**

As an example, a Method 2 direct well yield test conducted on a 2-inch diameter test well determined well yield in a confined aquifer to be 110 gpd. A conversion factor to estimate the equivalent well yield from a 4-inch diameter well can be obtained from Table C1.
For this case, the test well diameter is 2-inches, the equivalent well diameter to be evaluated is 4 inches, and the groundwater-bearing unit is confined, corresponding to a correction factor of 1.08 from Table C1. The well yield determined from a Method 2 direct well yield test procedure ($Q_{\text{test}} = 110 \text{ gpd}$) is then multiplied by the correction to obtain the equivalent yield from a well with a 4-inch diameter well screen:

$$110 \text{ gpd} \times 1.08 = 119 \text{ gpd}$$

This equivalent well yield can then used for purposes of evaluating the Class 3 yield boundary. In this example, the well yield of the GWBU (119 gpd) is less than 150 gpd for a 4-inch diameter well (or equivalent), corresponding to a Class 3 groundwater resource.
ATTACHMENT D

References


