GUIDANCE DOCUMENTS

William Feathergail Wilson, PG 21

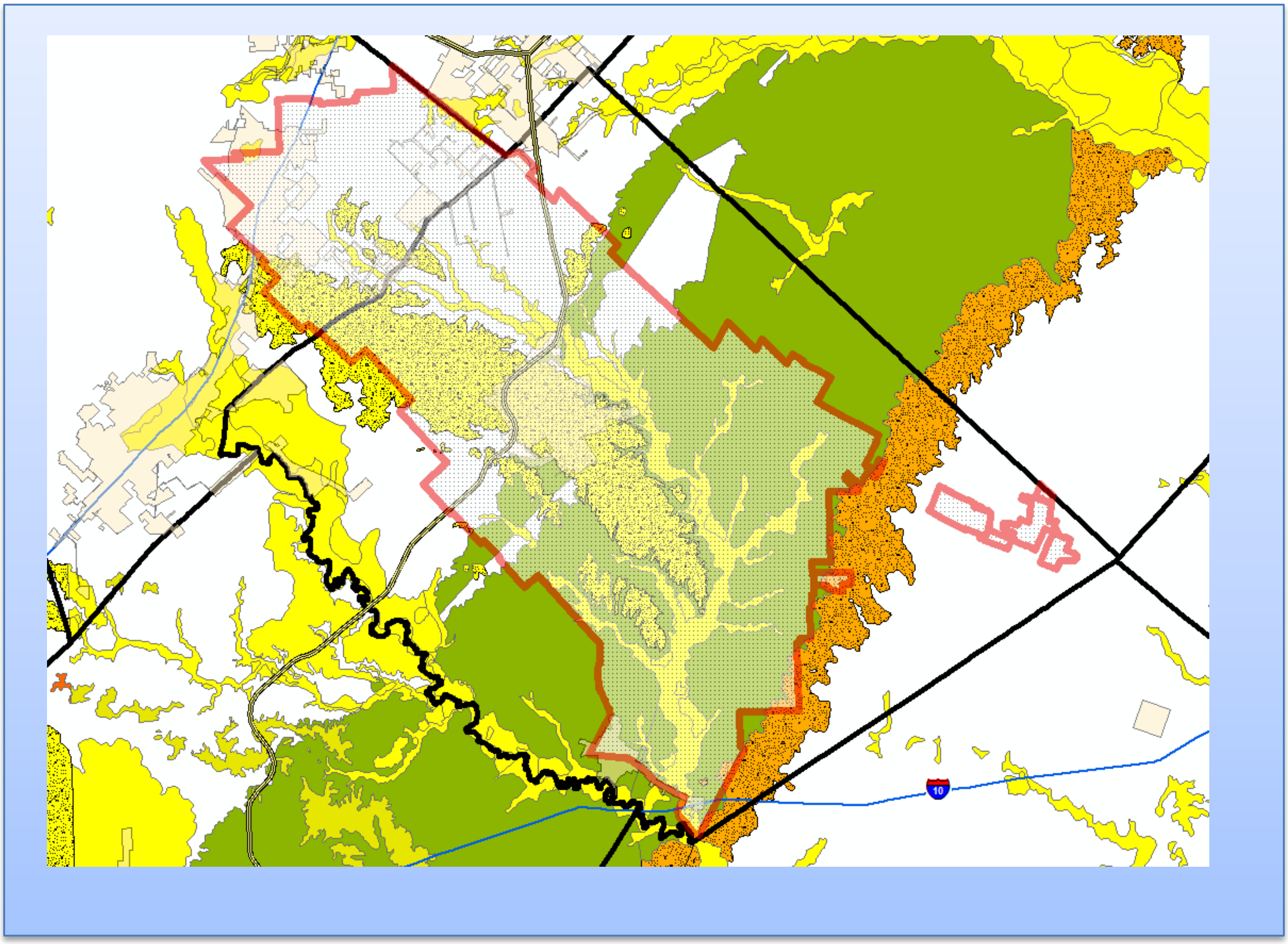
20012 PCCD

RULES

MITIGATION PLAN

MANAGEMENT PLAN

DROUGHT PLAN



The map depicts the surface expression of the major aquifers in the PCCD area.

- Leona Gravel: stippled yellow
- Alluvial: light yellow
- Wilcox: light tan
- Carrizo: light orange

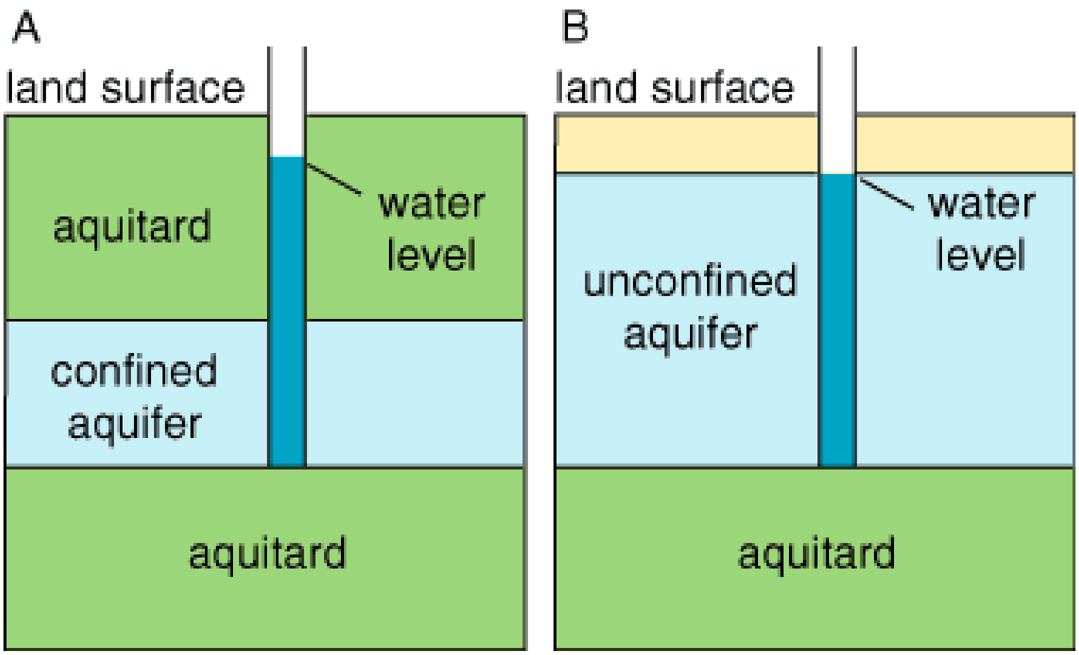
A deep potential aquifer does come to the surface and is known as the Lower Trinity or Hosston Formation. This potential aquifer parallels the Hays-Caldwell County boundary.

GROUNDWATER PRINCIPLES

Groundwater is intimately associated with surface water via recharge and discharge into and out of the subsurface.

Two types of groundwater are recognized:

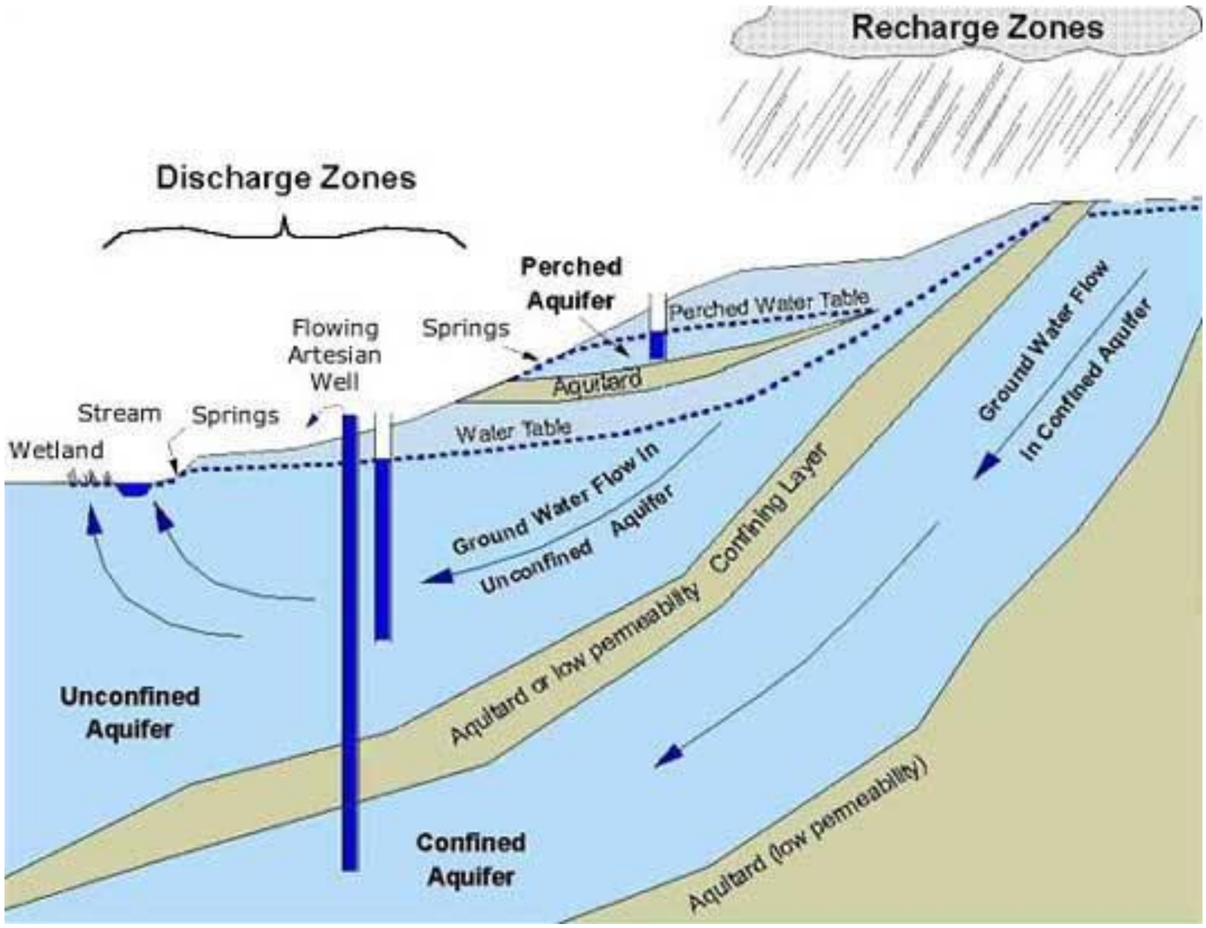
- Unconfined
- Confined

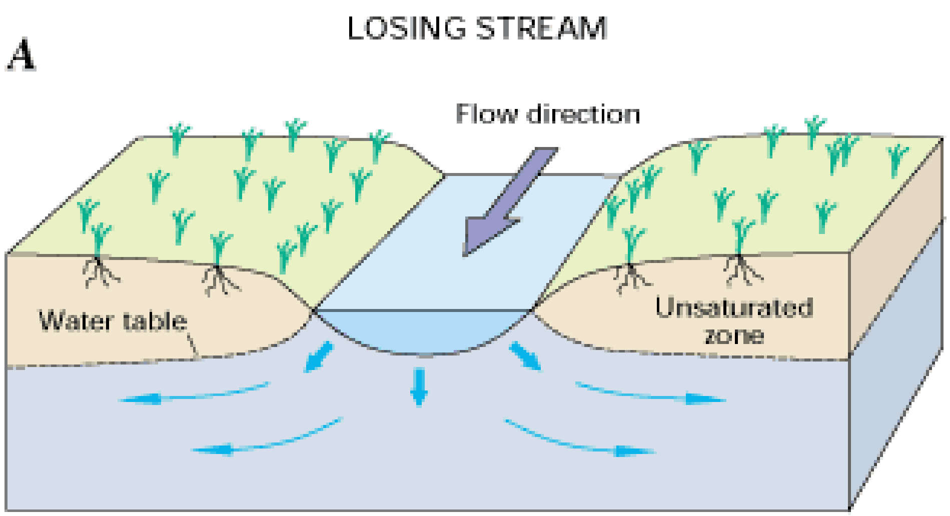


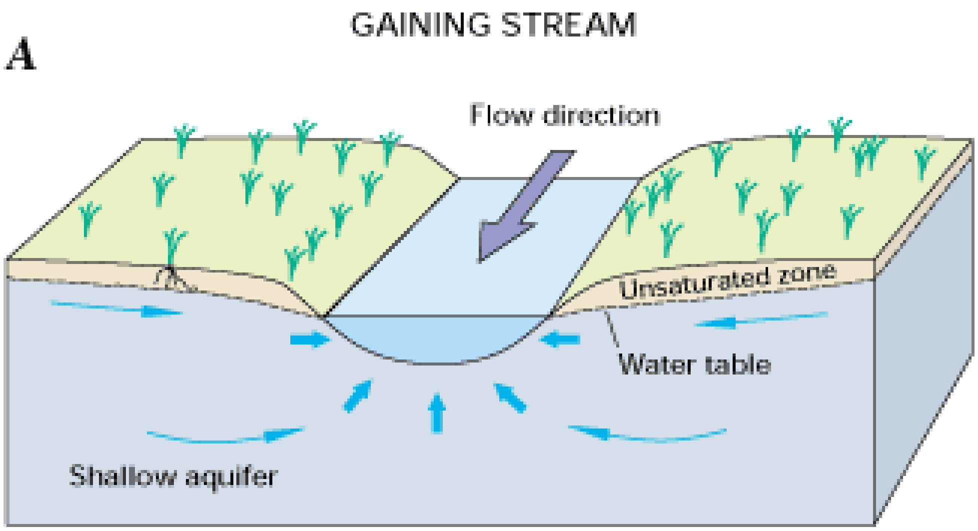
An aquitard is relatively impervious clay that retards vertical groundwater flow.

An aquitard is not present above an *unconfined* aquifer.

The Leona Gravel and the Alluvial sands along the PCCD streams are examples of *unconfined* aquifers. The Wilcox and Carrizo are both *confined* and *unconfined* depending upon their location.

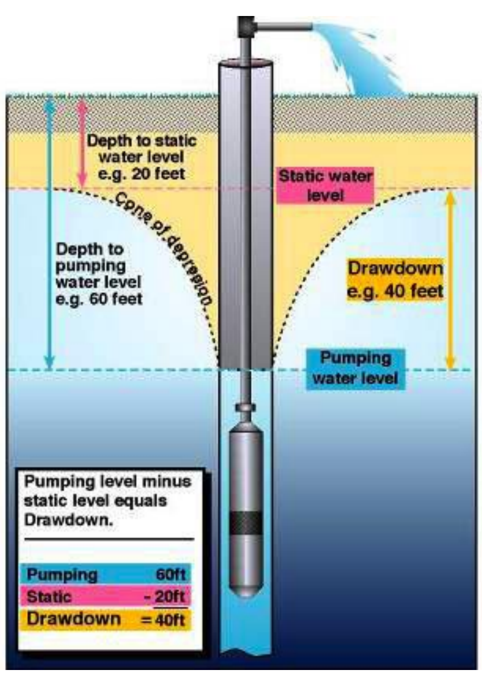

Recharge Zones
Discharge Zones
Perched
Aquifer
Perched Water Table
Flowing
Artesian
Well
Springs
Aquitard
Stream
Springs
Wetland
Water Table
Ground Water Flow in
Unconfined Aquifer
Confining Layer
Ground Water Flow
in Confined Aquifer
Aquitard or low permeability
Unconfined
Aquifer
Confined
Aquifer
Aquitard (low permeability)


LOSING STREAM
A
Flow direction
Water table
Unsaturated
zone



Groundwater along the Plum Creek watershed is both a losing and gaining stream dependent upon the surface geology and topography. For example, the Leona Gravel is topographically higher than Plum Creek and Leona springs feed into the Plum Creek. As Plum Creek crosses the Wilcox outcrop, it loses water into the underlying sands.

A pumping well creates a *drawdown cone of depression*.



As the well continues to pump, the cone of depression spreads out to a greater distance.

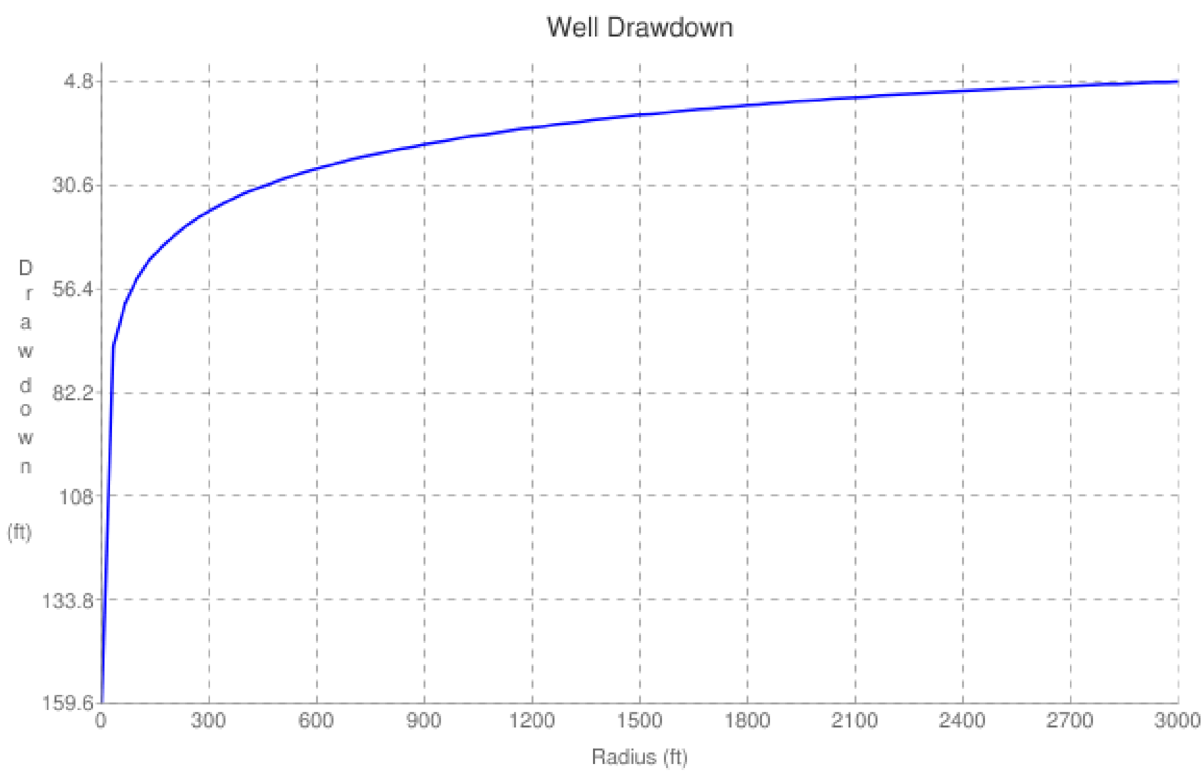
Theis Equation Calculator

Calculation

Radius, (r)	1500	Foot
Storage Coefficient, (S)	3.0E-4	
Transmissivity (T)	2244	GPD/ft
Time (t)	5	Days
Discharge, (Q)	150	GPM
◉ Drawdown, (s)	13.15	Foot

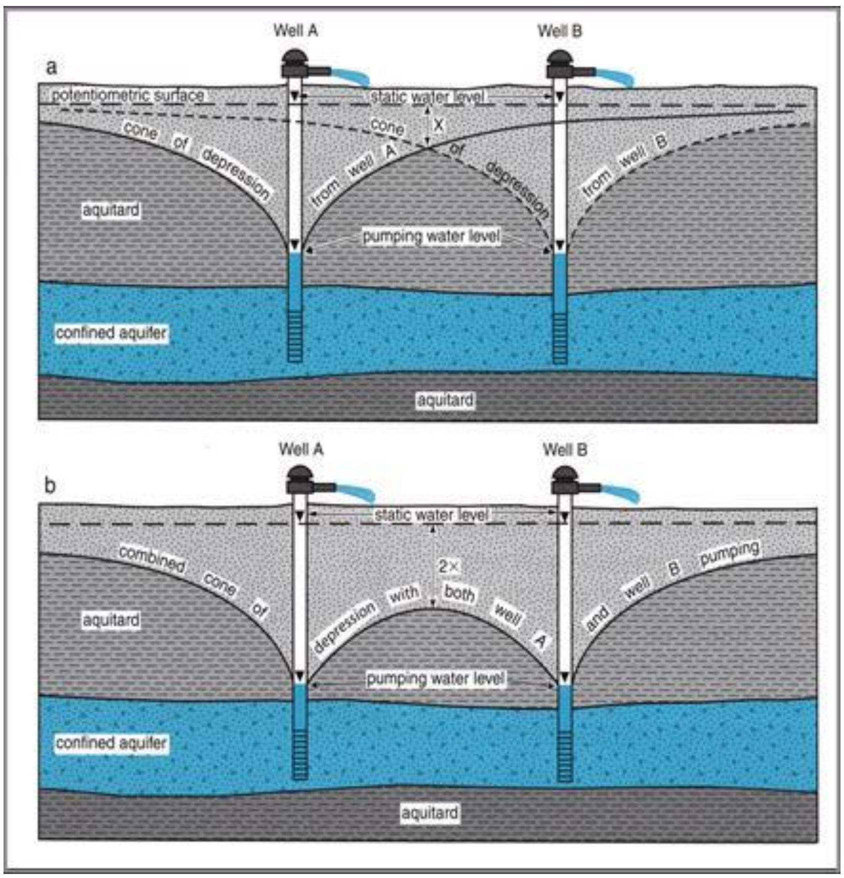
Function Parameters

u =1.87* r^2*S/(T*t) for default units	0.1125
Well Function, W(u)	1.7169994574225584



This figure shows a drawdown radius of 1,500 feet from a pumping well after 5-days of production at a rate of 150 gallons per minute (GPM). The drawdown is shown at varying distances out to 3,000 feet. Calculations can be made by varying the input parameters.

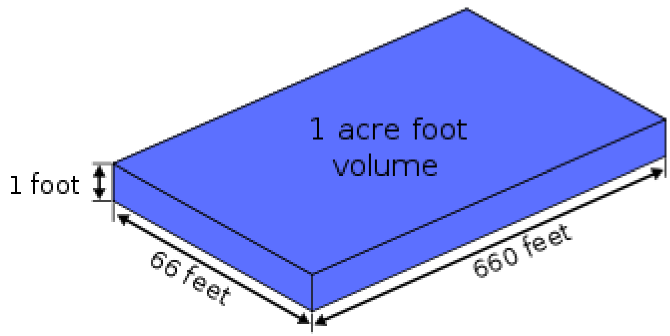
For example, suppose you own 50-acres and you drill a permitted well on the edge or corner of your property. Utilizing this figure you would be draining groundwater from your property as well as your neighbor's property. The 2011 State of Texas Legislative session passed SB-332, which states you own the groundwater beneath your property. ***PCCD can furnish you estimates of the cone of depression from your permit request.***



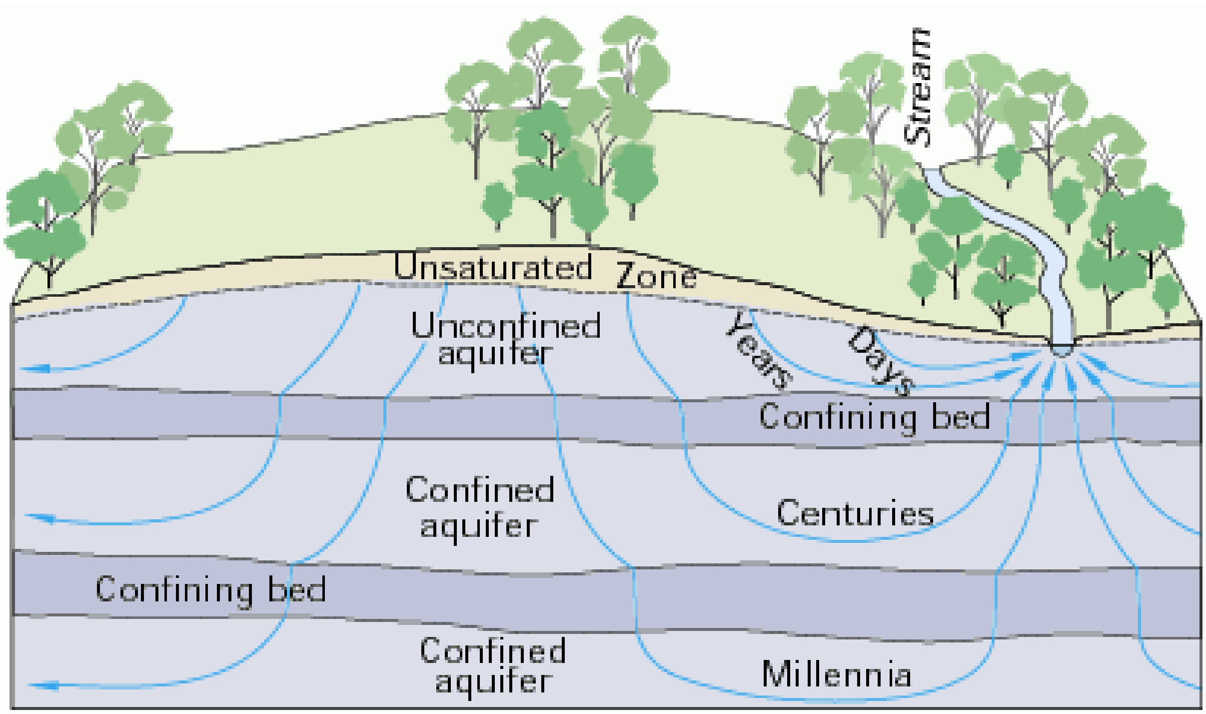
If wells are drilled too close to each other, they can interfere with each other and increase the cone of depression. This figure depicts two wells pumping from a confined aquifer

GROUNDWATER TERMS

Acre Foot: is 1-acre of groundwater, 1-foot deep



Hydraulic Conductivity: is a measure of how fast groundwater is moving through and aquifer on a per unit area expressed by the symbol K.



Transmissivity: is a measure of K times the saturated thickness of the aquifer.

Storage Coefficient: is a unitless number used to calculate the amount of groundwater that is stored in the aquifer at any one instant in time in three dimensions.

- *All of these numbers may be derived from pump tests or they may be obtained averages from the GAM's furnished by the TWDB.*

- *Carrizo-Wilcox GAM averages:*
    - *Storage Coefficient = 3.0 E-4*
    - *Transmissivity = 2244 GPD/foot*

Averages are deceptive over large areas. The Storage Coefficient has more average validity when applied to sand and sandstone than the Transmissivity number, which is more site-specific. However, SB-660 enacted in the 2011 State of Texas 82nd Legislative session demands the use of *"modeled"* numbers for groundwater management.

If challenged, the burden of proof is set upon the challenger and may involve considerable expense. At least three monitoring wells would have to be drilled and a formal pump test would have to be initiated.

GEOLOGY

REPORT
DOCUMENTS

GROUDWATER ESTIMATES BENEATH ACREAGE

William Feathergail Wilson, PG 21

May, 2012

The annual amount of groundwater available beneath a given parcel of property can be estimated from the following procedures:

- Pump tests
    - Hydraulic conductivity
    - Transmissivity
    - Storage coefficient
- Estimates of storage coefficients

Storage coefficients in confined aquifers generally range from 1E-3 to 1E-5 and average 1E-4. Thus, estimates can be made by assuming 3.0E-4 as a confined or semi-confined aquifer for a storage coefficient.

These estimates do not take into consideration sustainable recharge. That can be estimated from annual rainfall and total withdrawal on an annual basis or expressed as managed available groundwater.

The following equations allow such estimates:

$$GW = (Sc\,Rc\,Aq_t\,Ac)365 = acre\ feet / year$$

GW: annual available groundwater

Sc: Storage coefficient (3.0E-4)

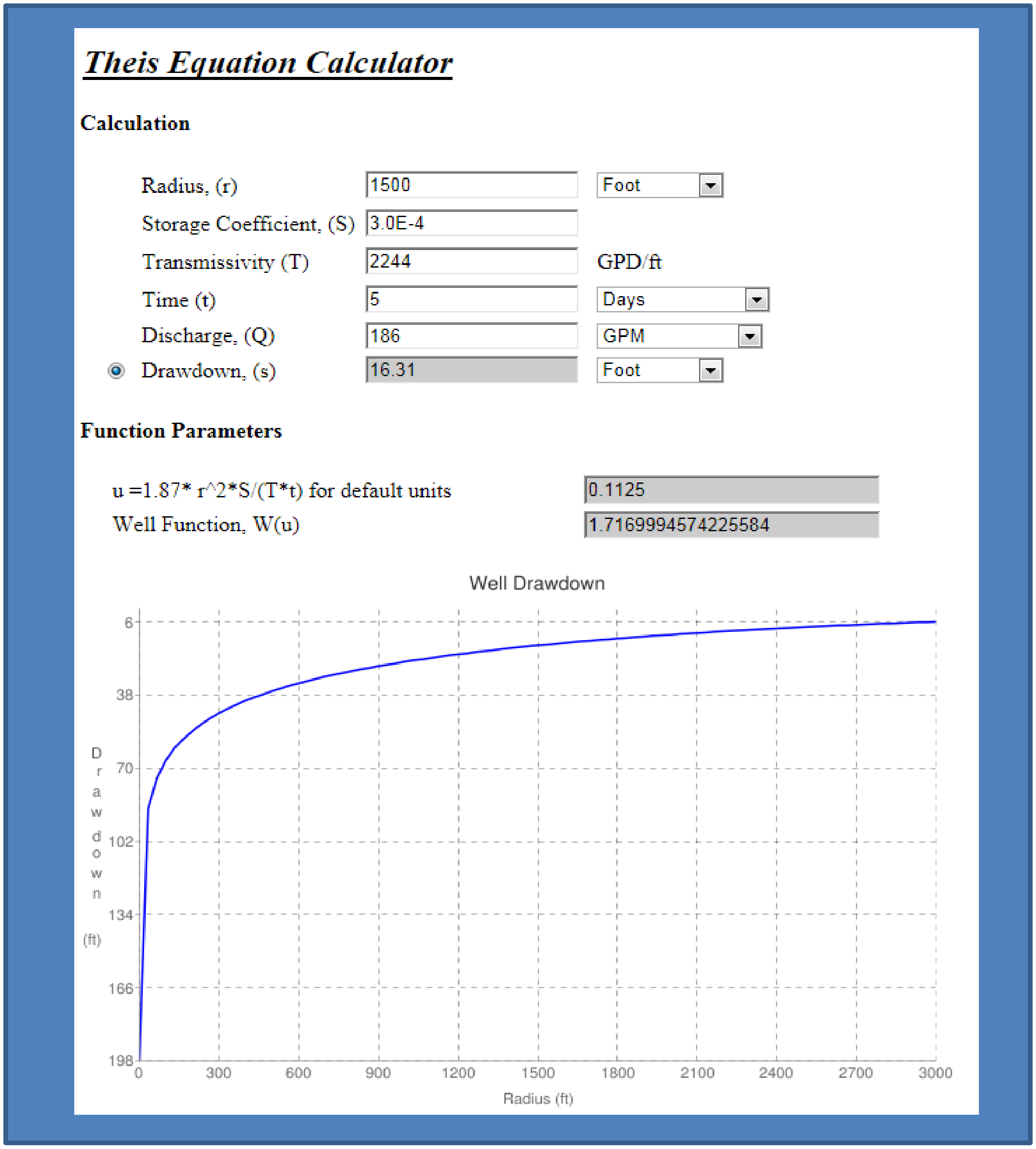
Rc: Recovery % (0.25)

$Aq_{t:}$: Saturated aquifer thickness

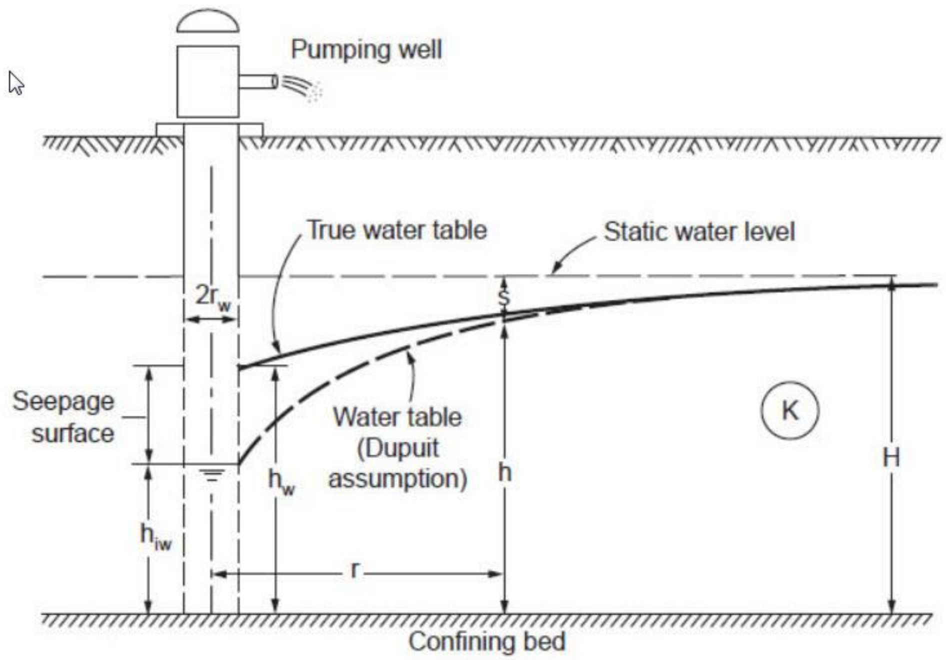
Ac: Surface acreage

This equation does not consider the radius of influence outside the boundaries of the property. An estimate of this can be obtained from an online calculator.

http://www.icalcul8.com/theis.php



This is the average drawdown for 300 acre feet in the Carrizo-Wilcox utilizing published GAM averages. Note: 300 acre feet is the PCCD rule limit.



$$u_a = r^2 S/(4Tt)$$

$$W(u) = -0.577216 - \ln u + u - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} - \cdots$$

$$s(r,t) = [Q/(4\pi T)] \int_u^{\infty} (e^{-z}/z)\,dz = [Q/(4\pi T)]\,W(u)$$

Modeled parameters may be obtained from the Carrizo-Wilcox GAM or estimated from known pump test information within the Caldwell County Wilcox or Carrizo areas.

The above analytical method is only applicable to ***confined*** aquifer areas. The Leona gravels and the stream vectored Alluvial aquifers will require higher Sc numbers such as 1.5E-2 or 1.5E-3 and higher T values since these aquifers are

unconfined. The same analytical method and equations can be applied to both confined and unconfined aquifers.

For the purposes of PCCD rules, estimate tables could be constructed or just place this method within the rules with simple instructions and average numbers.

Transmissivity is often expressed in other units and conversion factors should be provided within the rules.

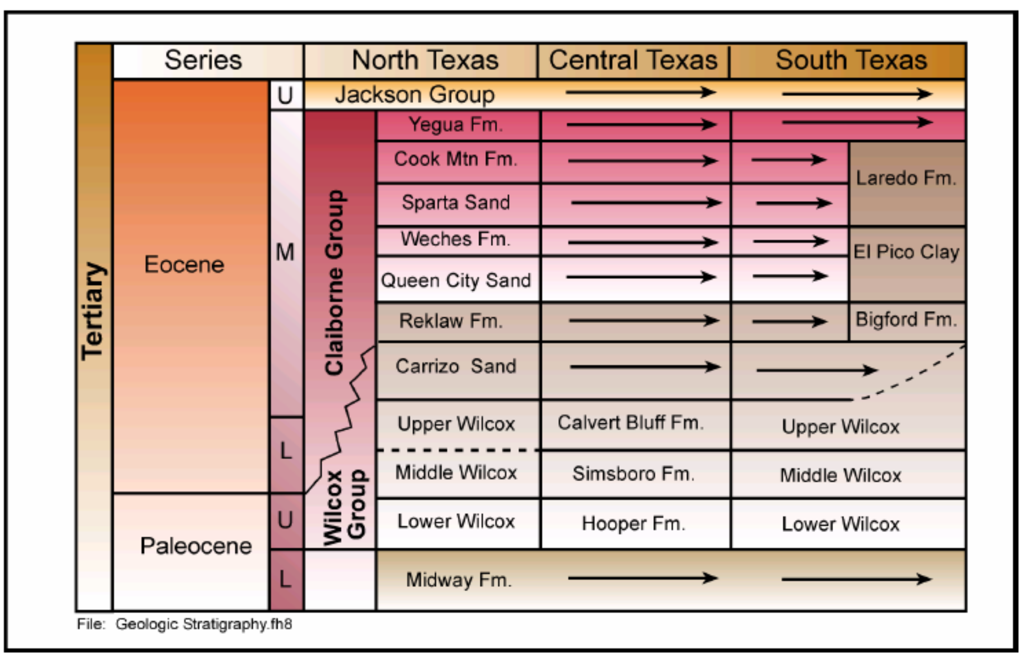
T= 1ft^2/min = 1.077 x 10^4 (GPD/ft)

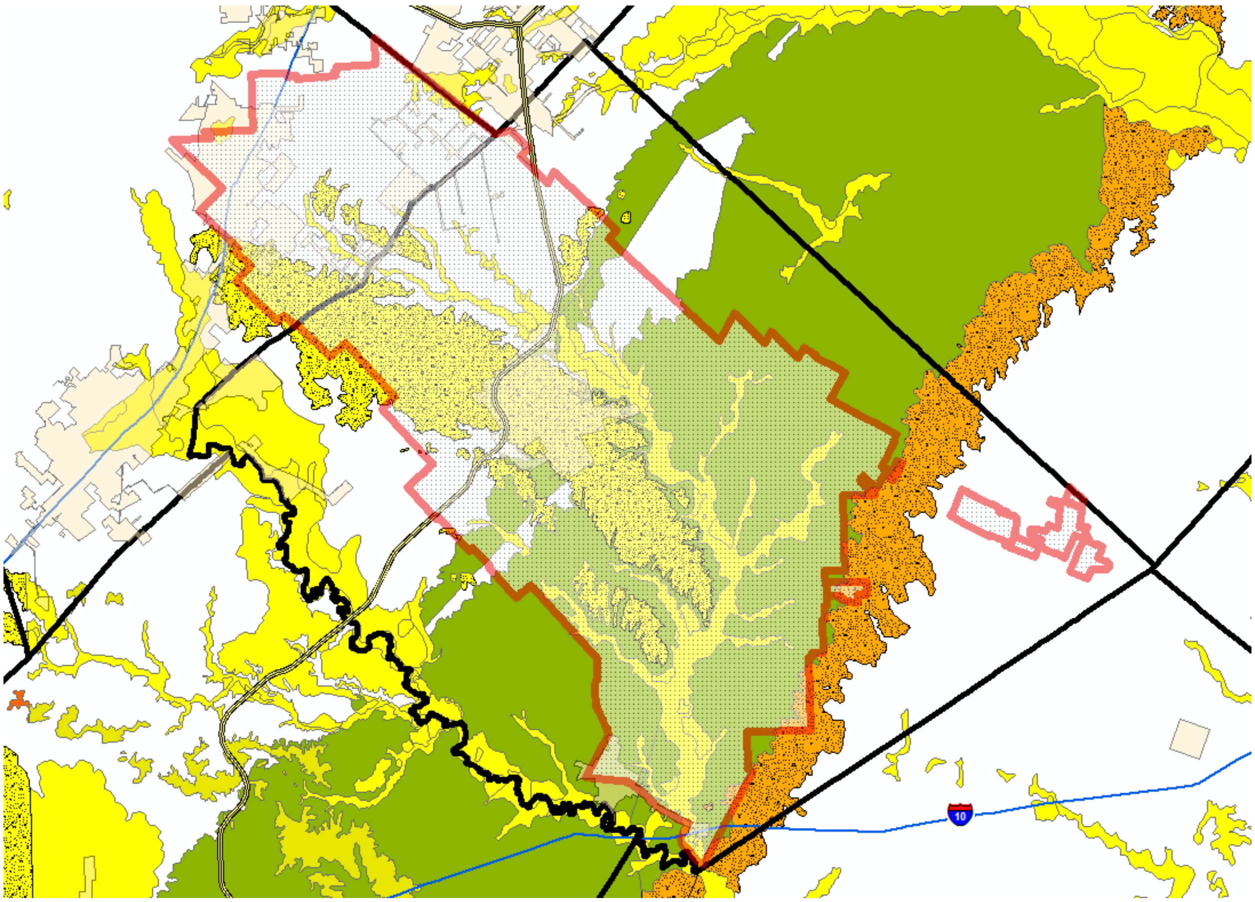
T=1ft^2/day =7.480 (GPD/ft)

The Carrizo-Wilcox Aquifer in Texas

Scott Jones

Spring 2008

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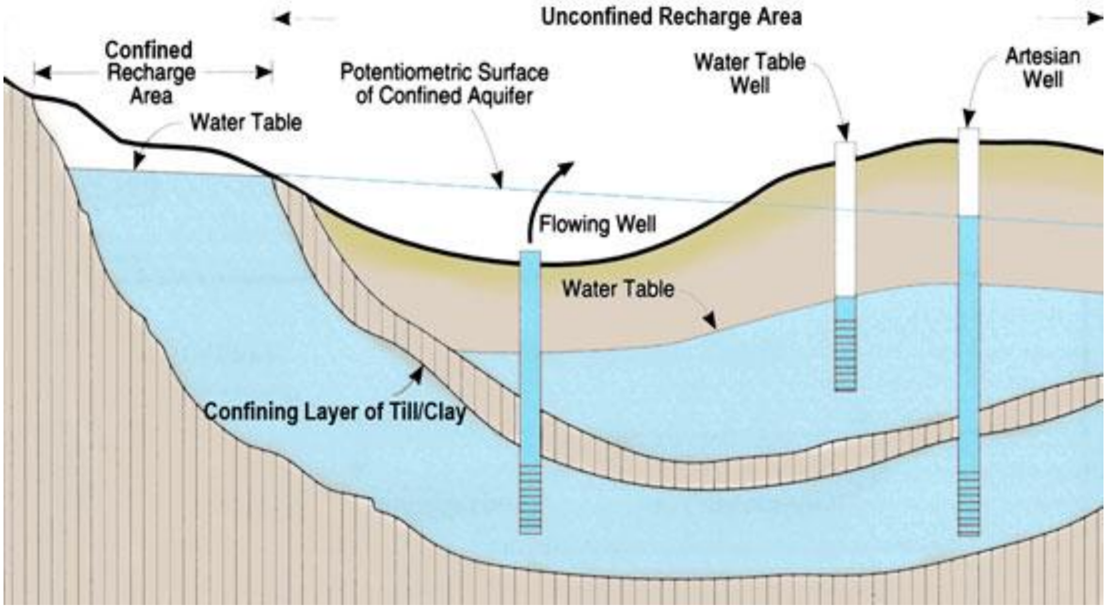

Unconfined Recharge Area
Confined Recharge Area
Potentiometric Surface of Confined Aquifer
Water Table Well
Artesian Well
Water Table
Flowing Well
Water Table
Confining Layer of Till/Clay


STATE OF TEXAS
WM. FEATHERGAIL WILSON
GEOLOGY
21
LICENSED
PROFESSIONAL GEOSCIENTIST

GEOLOGY OF BRACKISH WATER

BY

William Feathergail Wilson
Texas PG 21
May, 2012

INTRODUCTION

Brackish water is defined at various levels of Total Dissolved Solids. The most common demarcation is set at > 1,000 parts per million (ppm) or 1,000 mg/liter.

The following table is referenced in the PCCD Rules.

PCCD Definition Water Classes	Total Dissolved Solids (mg/l)
Fresh	<1,000
Slightly saline	1,000 to 3,000
Brackish	1,001-10,000
Very Saline	10,000-35,000
Sea Water	35,000
Brine	> 35,000

USGS: Davis & De Wiest (1996). Subsurface saline water has been found as high as 400,000 mg/l. Most subsurface brine ranges between 50,000 and 200,000 mg/l.

There are no set rules as to TDS classifications. Many Texans drink water that falls between 500 and 1,000 ppm despite the EPA safe drinking water standard definition of 500 ppm. Cattle balk at TDS levels above 3,000 ppm.

Brackish and saline water will become increasingly more important to GCDs in the near future due to the following factors:

- Desalination will become a necessity
- Oil & Gas Injection exempt wells will seek cheaper shallow injection zones and begin to compete with desalination
- GCD's will be forced into regulation of brackish water and compete with TRRC exempt usage for hydrofracing

TRCC EXEMPT WATER WELLS

RAILROAD COMMISSION of TEXAS

WATER USE IN ASSOCIATION WITH OIL AND GAS ACTIVITIES REGULATED BY THE RAILROAD COMMISSION OF TEXAS

1. RAILROAD COMMISSION OF TEXAS JURISDICTION

Generally, under Texas Natural Resources Code, Title 3, and Texas Water Code, Chapters 26 and 27, the Railroad Commission of Texas (Commission) has jurisdiction activities associated with the exploration, development, or production of oil or gas or geothermal resources, including transportation of crude oil or natural gas by pipeline. The Commission also has jurisdiction over surface mining for coal, uranium, and iron ore gravel.

2. USE OF FRESH WATER IN ASSOCIATION WITH OIL AND GAS ACTIVITIES

Water is used in association with many oil and gas activities, including use (in general order of relative volume) as a supplemental fluid in enhanced recovery of petroleum resources; during drilling and completion of an oil or gas well; during workover of an oil or gas well; during solution of underground salt in brine mining or hydrocarbon storage cavern creation; as gas plant cooling and boiler water; as hydrostatic test water for pipelines and tanks; as rig wash water; as coolant for internal combustion engines for rigs, compressors, and other equipment; for sanitary purposes; and for laboratory purposes.

The largest volume of water is used in enhanced recovery. The following table indicates injected volumes of total fluids (produced water, fresh makeup water, and other fluids) relative to estimates of total injected volumes of fresh water. Note that the trend for using fresh injection makeup water is declining. Most fresh water is injected for enhanced recovery in Commission Districts 8 and 8A in West Texas. The 1996 estimate for fresh water injected for those two districts was 252 million barrels.

Year	Estimate of fresh/brackish	Estimate of produced	TOTAL Estimated

	water (in million barrels)	water (in million barrels)	Volume of Fluids injected (in million barrels
CY 1998	316	6,000	6,316
CY 1999	276	5,600	5,876
CY 2000	254	5,900	6,154
CY 2001	212	5,900	6,112

The next largest volume of water is used during the drilling and completion of oil and gas wells. Water is used during drilling for drilling fluid preparation and make-up water, for completion fluids, including cementing, in well stimulation, as rig wash water, as coolant for internal combustion engines; and for sanitary purposes.

Fresh water is used in oil and gas well stimulation. Stimulation methods include acidizing and/or fracturing. In order to be able to produce gas at volumes and rates that are economical, reservoirs with low permeability must be treated. One method of treatment to increase permeability is fracture treatment or "fracing." Conventional fracture technology increases permeability as a result of pumping frac fluid, which generally consists of a viscous gelled fluid, and which creates an increase in the available surface area by creating fractures that are "propped up" or held open by the propping agents in the frac fluid.

Hydraulic fracturing consists of pumping into the formation large volumes of fresh water that generally has been treated with a friction reducer, surfactant and clay stabilizer, and that contains sand. Hydraulic fracturing maximizes the horizontal length of the fracture while minimizing the vertical fracture height. The fractures, which are held open by the sand, result in increased surface area, which further results in increases in the desorption of the gas from the shale and increases in the mobility of the gas. The result is lower completion costs and faster recovery of a larger volume of the gas-in-place. The volumes injected during hydraulic fracturing treatment can range from 70,000 barrels in a vertical well to over 90,000 barrels in a horizontal well. Fracing, where necessary, generally takes place immediately after drilling and periodically during the life of the well.

3. REGULATION OF SURFACE WATER IN TEXAS

The industries regulated by the Commission use both surface water and ground water for their activities. In Texas, water flowing in Texas creeks, rivers, and bays is owned and managed by the State. Anyone who diverts such surface water must have authorization – or a water right -- from the State of Texas through the Texas Commission on Environmental Quality (TCEQ) (Texas Water Code, Chapter 11, relating to Water Rights). Therefore, a person who withdraws surface waters for mining, construction, and oil or gas activities must obtain a water rights permit from TCEQ.

An applicant may apply for a Temporary Water Right permit for short-term use of surface water. Temporary Water Rights permits authorizing use of 10 acre feet or less and for one year or less may be issued by a TCEQ Regional Office. In times of drought, the TCEQ may suspend all temporary water rights permits.

Applicants who seek to use more than 10 acre-feet of water or who seek a term of more than one year (up to a maximum of three years) must apply through the TCEQ Water Rights Permitting Team in Austin. TECQ forms, fees, contacts, and other water rights information may be found on the TCEQ website (www.tceq.state.tx.us).

4. REGULATION OF GROUND WATER IN TEXAS

A. Regulations of the Railroad Commission of Texas.

Much of the water used in association with oil and gas activities, particularly the water used in enhanced recovery, is saline or brackish water. With regards to enhanced recovery more than 90 percent of the water used is actually highly saline to brackish water produced from the same formations where the oil fields are located. A very small percentage of the water used for enhanced recovery is fresh water or slightly saline water produced from outside sources as needed to replace the volume of oil removed. Saline or brackish water is drawn from underground reservoirs that are below the base of usable quality water. The Railroad Commission requires a permit for wells associated with oil and gas activities that draw such water from formations below the base of usable quality water.

The Commission's Statewide Rule 5 (16 TAC §3.5) requires a Commission drilling permit to drill an injection water supply well that penetrates the base of usable quality water. Statewide Rule 13 (16 TAC §3.13) requires that an injection supply water well that penetrates the base of usable quality water be completed in accordance with the criteria in the rule, and the injection supply water well must be plugged in accordance with Statewide Rule 14 (16 TAC §3.14).

When a fresh water well, whether the well is a rig supply well or an injection water supply well, is drilled above the base of usable quality water and fresh water is used, regulations other than those of the Commission apply.

B. Regulations of the Texas Department of Licensing and Regulation.

Effective September 1, 2003, the Texas Department of Licensing and Regulation (TDLR) regulates Water Well Drillers under the Texas Occupations Code, Chapter 1901. Rig supply wells must be drilled by a licensed Water Well Driller; however, Chapter 1901 excludes from the definition of "water well" "an injection water source well regulated under §91.101 of the Natural Resources Code." The Water Well Driller must submit drilling logs and other required information to the TDLR and the Texas Water Development Board. The completion and plugging of such wells must comply with TDLR regulations. The GWCDs have the authority to enforce the plugging regulations for abandoned or deteriorated water wells within their boundaries.

C. Regulations of Groundwater Conservation Districts.

In Texas, groundwater ownership rights are subject to regulation and control by the courts and the State Legislature. Groundwater may be managed individually by landowners under the rule of capture, or collectively by landowners and groundwater conservation districts (GCDs). Under the "Rule of Capture," landowners may pump as much water as they choose, without liability to surrounding landowners who might claim that the pumping is depleting their wells. There are very few restrictions to the rule of capture.

The Texas Legislature authorized the creation of GCDs as the State's preferred method of groundwater management (Texas Water Code, Chapter 36). These districts are empowered and charged to conserve, preserve, protect, recharge, and prevent waste of groundwater resources within their boundaries. GCDs may be created through a special legislative act, a landowner petition process to the Texas Commission on Environmental Quality (TCEQ), a landowner petition process to join an existing GCD, or TCEQ initiative in a priority groundwater management

area (PGMA). Additional information regarding groundwater management can be located at the following:
http://www.tgpc.state.tx.us/GWManagement.htm

Chapter 36 specifically does not apply to production or injection wells drilled for oil, gas, sulphur, uranium, or brine, or for core tests, or for injection of gas, saltwater, or other fluids, under permits issued by the Railroad Commission. However, it does apply to water wells, including injection water source wells ("water wells used to supply water for activities related to the exploration or production of hydrocarbons or minerals" (§36.117(l)).

Under Texas Water Code §36.117, there are certain exemptions, exceptions, and limitations to Chapter 36. In addition to exemptions for small volume livestock and poultry and domestic water wells, there are certain exceptions for temporary rig supply wells and limitations on injection water supply wells used in association with oil and gas activity, as well as water wells associated with surface mining activity.

Section 36.117 includes a permit exception for temporary rig supply wells. A GCD may not require a permit for the drilling of a temporary rig supply well ("drilling of a water well used solely to supply water for a rig that is actively engaged in drilling or exploration operations for an oil or gas well permitted by the Railroad Commission of Texas provided that the person holding the permit is responsible for drilling and operating the water well and the well is located ***on the same lease or field*** associated with the drilling rig" (§36.117(b)(1)). However, a rig supply water well must be registered in accordance with GCD rules and must be equipped and maintained to conform to the GCD's rules requiring installation of casing, pipe, and fittings to prevent the escape of ground water from a groundwater reservoir to any reservoir not containing ground water and to prevent the pollution or harmful alteration of the character of the water in any groundwater reservoir (§36.117(h)). The driller of a rig supply well must file the drilling log with the GCD (§36.117(i)). In addition, the GCD may require a water well originally drilled for the purpose of rig supply to be permitted by the GCD and to comply with all GCD rules if the purpose of the well no longer is solely to supply water for a rig that is actively engaged in drilling or exploration operations for an oil or gas well permitted by the Railroad Commission (§36.117(d)). And finally, the well must be plugged in accordance with GCD regulations.

Section 36.117 also includes a limitation on injection water supply wells. Although Chapter 36 applies to injection water source wells, Section 36.117 prohibits a GCD from denying an application for a permit to drill and produce water for hydrocarbon production activities (an injection supply water well) if the application meets all applicable rules as promulgated by the GCD (§36.117(g)).

The following tables outline the regulations relating to water wells drilled for water to be used in oil and gas activities in Texas.

Section 36.117 also includes a permit exemption for water wells drilled in association with surface mining. A GCD may not require a permit issued by the GCD for the drilling of a water well authorized under a permit issued by the Railroad Commission under Chapter 134, Natural Resources Code, or for production from such a well to the extent the withdrawals are required for mining activities regardless of any subsequent use of the water. However, such a well must be registered in accordance with GCD rules and must be equipped and maintained so as to conform to the GCD's rules requiring installation of casing, pipe, and fittings to prevent the escape of groundwater from a groundwater reservoir to any reservoir not containing groundwater and to prevent the pollution or harmful alteration of the character of the water in any groundwater reservoir, and the driller of such a well must file with the GCD a copy of the drilling log. Furthermore, a GCD may require such a well to be permitted by the GCD and to comply with all GCD rules if the withdrawals from such a well are no longer necessary for mining activities or are greater than the amount necessary for mining activities specified in the permit issued by the Railroad Commission.

REQUIREMENTS FOR WATER WELLS ASSOCIATED WITH OIL AND GAS ACTIVITIES IN TEXAS

TCEQ = Texas Commission on Environmental Quality
RRC = Railroad Commission of Texas
GCD = Groundwater Conservation District
TDLR = Texas Department of Licensing and Regulation

Rig Supply Wells that DO Not Penetrate the Base of Usable Quality Water		
Agency	**Requirement**	**Cite**

TDLR	Rig supply water well must be drilled by Licensed Water Well Driller.	§1901.151 Texas Occupations Code
	Driller must make and keep a well log in accordance with TDLR rules and forms and must send a copy of the log to TDLR and TCEQ. Log must include: 1. the depth, thickness, and character of strata penetrated; 2. the location of water-bearing strata; 3. the depth, size, and character of casing; and 4. any other information required by TDLR.	§1901.251, Texas Occupations Code
	Driller must complete the rig supply water well in accordance with TDLR standards and procedures.	§1901.253, Texas Occupations Code
	Landowner or operator of abandoned or deteriorated water well must plug or cap the well within 180 days. (NOTE: A GCD has the authority to enforce this section.) Driller, pump installer, or owner who plugs a rig supply water well must submit plugging report to GCD and TDLR.	§§1901.254, 1901.255, and 1901.256, Texas Occupations Code
GCD	Rig supply water wells are exempt from GCD permitting requirements provided: • the rig supply water well is to be used solely to supply water for a rig that is actively engaged in	§36.117(b)(2), Texas Water Code

	drilling or exploration operations for an oil or gas well permitted by the RRC*; and • the person holding the permit is responsible for drilling and operating the water well and the well is located on the same lease or field associated with the drilling rig.	
	Rig supply well must be: • registered in accordance with GCD rules and • be equipped and maintained so as to conform to the GCD's rules requiring installation of casing, pipe, and fittings to prevent the escape of groundwater from a groundwater reservoir to any reservoir not containing groundwater and to prevent the pollution or harmful alteration of the character of the water in any groundwater reservoir.	§36.117(h), Texas Water Code
	Driller must submit the drilling log for the rig supply water well to the GCD.	§36.117(i), Texas Water Code
	The GCD may require a permit and compliance with all GCD rules if the exempted rig supply well no longer supplies water solely to a rig that is actively engaged in drilling or exploration operations for an oil or gas well permitted by the RRC.	§36.117(d)(1), Texas Water Code
	Groundwater withdrawn from an exempt rig supply water well that is subsequently transported outside the boundaries of the GCD is subject to	§§36.117(k), 36.122 and 36.205, Texas Water Code

	any applicable production and export fees.	

* The RRC interprets the phrase “a rig that is actively engaged in drilling or exploration operations for an oil or gas well permitted by the commission” to mean a drilling rig or a workover rig and interprets “exploration operations” to include well completion and workover, including hydraulic fracturing operations.

Rig Supply Wells that Penetrate the Base of Usable Quality Water		
Agency	**Regulation**	**Cite**
TDLR	A driller must notify TDLR and the landowner or person having a well drilled on encountering water injurious to vegetation, land, or other water and determining that the well must be plugged, repaired, or properly completed in order to avoid injury or pollution. The driller must ensure that the well is plugged, repaired, or properly completed under standards and procedures adopted by TDLR.	Chapter 28 Texas Water Code §1901.254

Injection Water Supply Wells that Do Not Penetrate the Base of Usable Quality Water		
Agency	**Requirement**	**Cite**
TDLR	Injection water supply well must be drilled by licensed water well driller.	§1901.151 Texas Occupations Code
	Driller must make and keep a well log in accordance with TCEQ rules and forms and must send a copy to the well owner, TDLR and TCEQ. The well log must include: 1. the depth, thickness, and character	§1901.251, Texas Occupations Code

	of strata penetrated; 2. the location of water-bearing strata; 3. the depth, size, and character of casing; and 4. any other information required by TDLR.	
	Driller must complete the well under TDLR standards and procedures.	§1901.253, Texas Occupations Code
	Landowner or operator of abandoned or deteriorated water well must plug or cap the well within 180 days. (NOTE: GCD has authority to enforce this section.) Driller, pump installer, or owner who plugs injection water supply well must submit plugging report to GCD and TDLR.	§§1901.254, 1901.255, and 1901.256, Texas Occupations Code
GCD	Jurisdiction of GCD applies to water wells, including water wells used to supply water for activities related to the exploration or production of hydrocarbons or minerals. Jurisdiction does not extend to production or injection wells drilled for oil and gas, or for core tests, or for injection of gas, saltwater, or other fluids, under permits issued by the RRC.	§36.117(l), Texas Water Code
	GCD permit required for injection water supply wells drilled for hydrocarbon activities associated with an oil or gas well drilled after September 1, 1985.	§36.117, Texas Water Code, enacted effective 09-01-1985.
	A GCD cannot deny an application for a permit to drill and produce water for	§36.117(g), Texas Water

	hydrocarbon production activities (injection water supply well) if the application meets all applicable GCD rules.	Code
	A GCD permit may regulate: 1. Spacing of wells from property lines or adjoining wells 2. Density 3. Production 4. Completion; and 5. Plugging A GCD permit may also require submission of certain information and assess production fees.	§§36.1131 and 36.116 §§36.120, §36.205 and 36.206, Texas Water Code
	Water well must be completed and plugged in accordance with TDLR rules.	§§1901.253, 1901.254, and 1901.255, Texas Occupations Code
	Report of well plugging must be submitted to the GCD and TDLR.	§1901.255, Texas Occupations Code

Injection Water Supply Wells that Penetrate the Base of Usable Quality Water		
Agency	**Regulation**	**Cite**
RRC	A RRC drilling permit is required to drill an injection water source well that penetrates the base of usable quality water.	§91.101, Texas Natural Resources Code 16 TAC §3.5
	Well must be cased and plugged in accordance with RRC regulations.	16 TAC §§3.13 and 3.14.

Note the paragraph outlined in large font "***<u>on the same lease or field</u>".***

The "same lease" may mean that if afresh or slightly saline water well is used off the lease is sold or moved, it will become subject to permit by a GCD. The Gulf Coast Evergreen district has interpreted this to be true and may not recognize the "field" portion of this rule.

The 17-million acre Eagle Ford Field may mean that all water wells drilled in any county used for hydrofracing or any injection well are not subject to any control by a GCD except registration. It is still unclear if the Eagle Ford play is a single field or a series of fields.

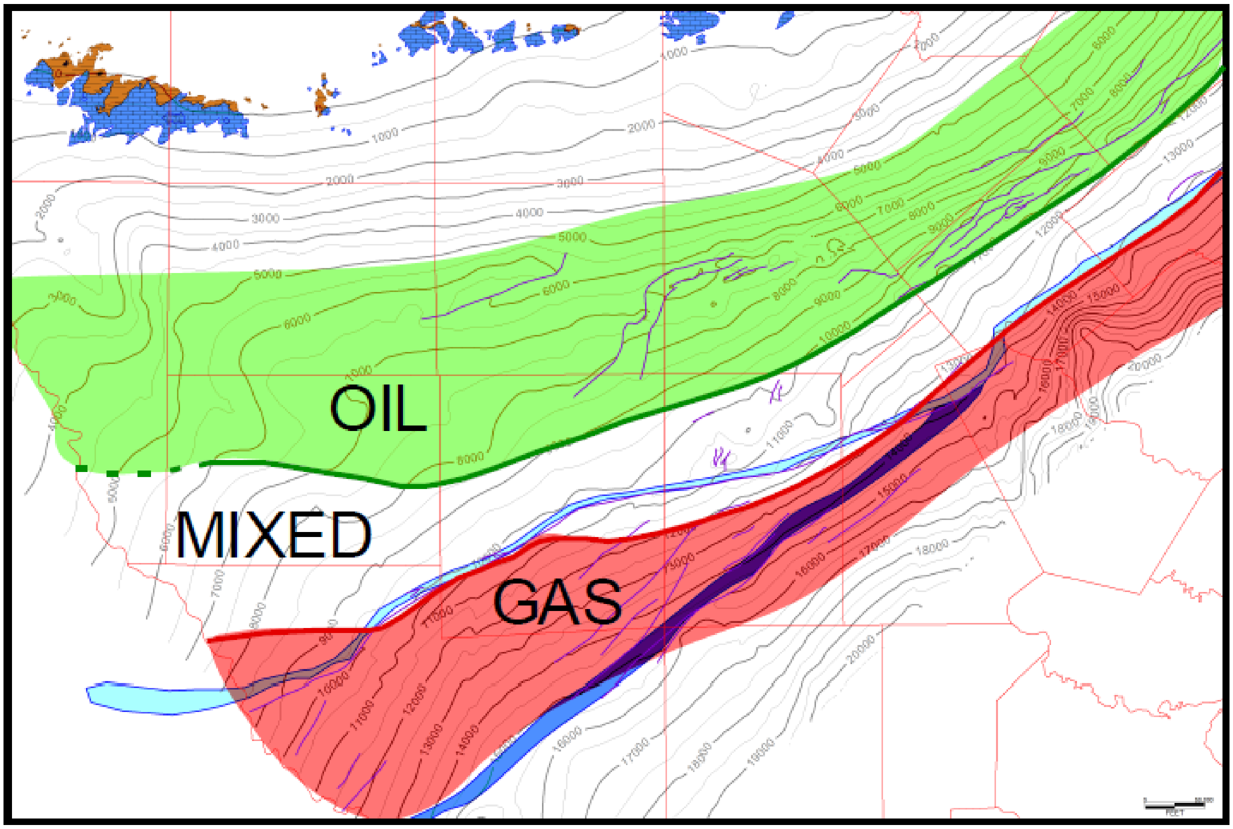
Another problem exists in the definition of "fresh water". The TWDB and the TCEQ view fresh water as equal to or less than 1,000 ppm. It is assumed that this is the official Texas break point.

Caldwell County contains more than 9,000 wells drilled for oil and gas. Many producing and abandoned wells have developed casing leaks, which created areas of higher than 1,000 ppm within fresh water zones in the Wilcox sands. These areas have created some undefined brackish water TRRC and other local and state agency problems. As long as they are not addressed, it may not be a problem.

As the Gulf Coast Pearsall play develops, it may follow the same conventions as the Eagle Ford. These two plays are both hydrofrac targets. The Pearsall will exceed the areas and counties covered by the Eagle Ford. There are some geochemical differences between the two plays. The Eagle Ford has proved to have three zones of production being:

- Natural gas only
- Natural gas and oil (condensate)
- Oil

Natural gas is now priced at less $4.00 per MCF, which has pushed the Eagle Ford play into the liquids geochemical window.



Eagle Ford production zones.

The deeper Pearsall play may follow the same pattern dependent upon geochemical factors.

Every oil and gas well ever drilled has its own optimum production rate. This statement is especially applicable to hydrofrac wells. Steep decline curves are common to over optimum production levels. That in return leads to re-fracing.

The average hydrofrac Eagle Ford well requires 6.1 million gallons of fresh to slightly brackish water which equates to 18.7 acre feet per well per hydrofrac. It is forecast that an additional 20,000-30,000 wells will be drilled over the next few decades focused on shale gas plays in the Texas Gulf Coast.

This may result in spending that will exceed $100 billion dollars. A few operators are beginning to advocate spending another $4billion on a desalination Gulf of Mexico pipeline into the shale gas plays.

Al of the major shale gas operators are in the initial investigative stages of recycling flowback water. The percentage of flowback varies from well-to-well and area-to-area and is largely site specific.

GCD BRACKISH WATER ISSUES

All of the GCD's will soon face brackish water issues as the population of swells and essentially doubles over the next few decades.

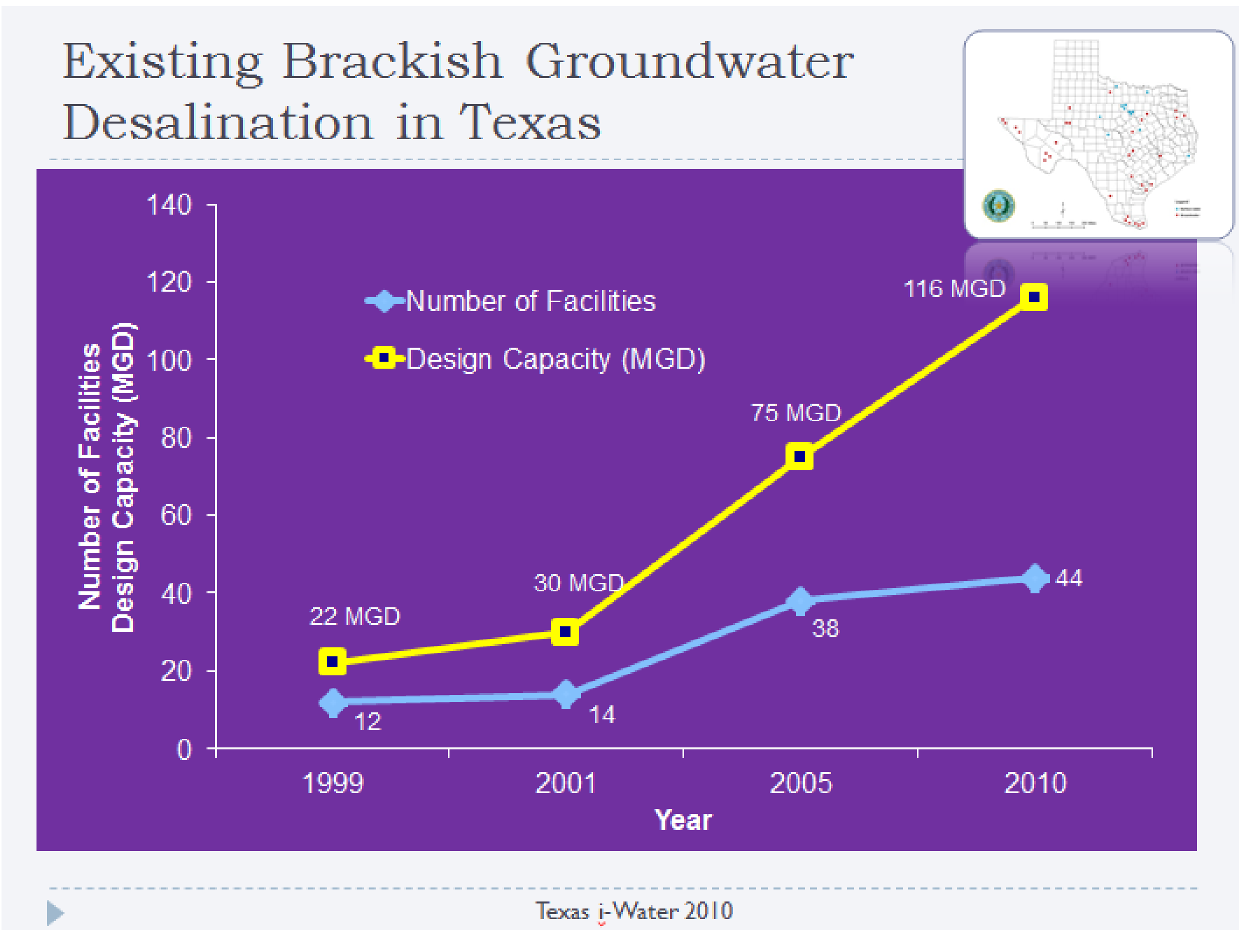


FIGURE 3.1. TEXAS STATE POPULATION PROJECTED TO 2060.

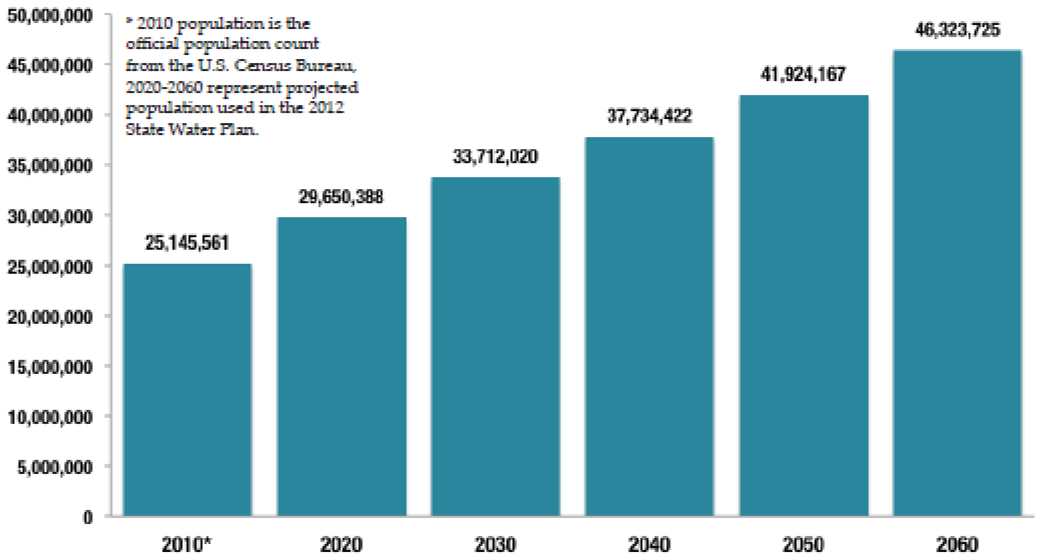


FIGURE 5.1. PROJECTED WATER EXISTING SUPPLIES (ACRE-FEET PER YEAR).

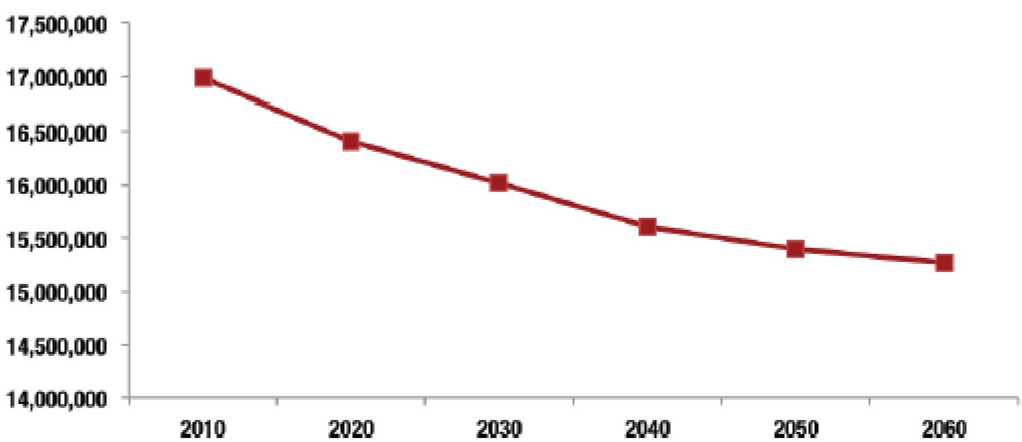


TABLE 3.1. TEXAS STATE POPULATION PROJECTIONS FOR 2010-2060

Region	2010	2020	2030	2040	2050	2060
A	388,104	423,380	453,354	484,954	516,729	541,035
B	210,642	218,918	223,251	224,165	223,215	221,734
C	6,670,493	7,971,728	9,171,650	10,399,038	11,645,686	13,045,592
D	772,163	843,027	908,748	978,298	1,073,570	1,213,095
E	863,190	1,032,970	1,175,743	1,298,436	1,420,877	1,542,824
F	618,889	656,480	682,132	700,806	714,045	724,094
G	1,957,767	2,278,243	2,576,783	2,873,382	3,164,776	3,448,879
H	6,020,078	6,995,442	7,986,480	8,998,002	10,132,237	11,346,082
I	1,090,382	1,166,057	1,232,138	1,294,976	1,377,760	1,482,448
J	135,723	158,645	178,342	190,551	198,594	205,910
K	1,412,834	1,714,282	2,008,142	2,295,627	2,580,533	2,831,937
L	2,460,599	2,892,933	3,292,970	3,644,661	3,984,258	4,297,786
M	1,628,278	2,030,994	2,470,814	2,936,748	3,433,188	3,935,223
N	617,143	693,940	758,427	810,650	853,964	885,665
O	492,627	521,930	540,908	552,188	553,691	551,758
P	49,491	51,419	52,138	51,940	51,044	49,663
TEXAS	25,388,403	29,650,388	33,712,020	37,734,422	41,924,167	46,323,725

Clearly all GCD's will have to consider desalination of slightly saline and brackish water as a source for municipal and rural use. This will entail altering portions of Rules, Management Plans and Mitigation Plans.

No GCD should ever cut off their rules at 1,000 ppm or any arbitrary depth. No potential aquifer should be considered "non-relevant" due to TDS, aquifer identification or depth. For example, GMA-10 considers the Trinity aquifers to be "non-relevant" due to TDS levels exceeding 3,000 ppm.

A few large areas of the Carrizo utilized for irrigation would be considered "non-relevant" under the same criteria.

The TWDB LP-214and Hydrogeologic Atlas No. 3 designates fresh-brackish-saline water in the following table:

Classification	**TDS mg/liter**
Fresh	1,000
Slightly Saline	1,000-3,000
Moderately Saline	3,000-10,000
Very Saline	10,000-35,000

A few West Texas aquifers are set between 5,000-10,000 mg/liter for irrigation and industrial uses which adds to the classification confusion.

TCEQ lists the Maximum Contaminant Limits for elements and molecules as TDS levels for reporting and clean-up.

Primary Constituent Levels		
Constituent	Symbol	MCL
Arsenic	As	0.05 mg/l
Barium	Ba	2.0 mg/l
Cadmium	Cd	0.005 mg/l
Chromium	Cr	0. 10 mg/l
Fluoride	F	4.0 mg/l
Lead	Pb	0.015 mg/l
Mercury	Hg	0.002 mg/l
Nitrate (as N)	NO_3 (N)	10.0 mg/l
Selenium	Se	0.05 mg/l
Gross Alpha	α	15 pCi/l
Gross Beta	β	50 pCi/l
Radium	$Ra^{226} + Ra^{228}$	20 pCi/l
Secondary Constituent Levels		
Chloride	Cl	300 mg/l
Copper	Cu	1.0 mg/1
Fluoride	F	2.0 mg/l
Iron	Fe	0.3 mg/l
Manganese	Mn	0.05 mg/l
pH	pH	≥7.0
Silver	Ag	0. 10 mg/1
Sulfate	$S0_4$	300 mg/l
Dissolved Solids	TDS	1,000 mg/1
Zinc	Zn	5.0 mg/l
Radon 222	Rn^{222}	300 pCi/l

Irrigation with TDS levels above approximately 1,000 mg/liter will build up salt within the soils to the point where they become unusable.

Conflicts will begin to arise over the definition of fresh, slightly saline and brackish water over TRRC casing rules.

Conflicts will arise over TRRC injection well depths and zones. One notable objection just surfaced recently in Victoria County.

Litigation will most certainly arise over slightly saline and brackish water uses as the conflicts arise.

Once again, GCD Rules, Policies, Management Plans and Mitigation Plans will become increasingly complex and important. These elements are the shields and transparent instruments to aid in the negation of challenge as well as conservation.

William Feathergail Wilson, PG 21

GEOLOGY OF CORRELATIVE RIGHTS

BY

William Feathergail Wilson
Texas PG 21
May, 2012

"The correlative rights doctrine is a legal doctrine limiting the rights of landowners to a common source of groundwater (such as an aquifer) to a reasonable share, typically based on the amount of land owned by each on the surface above."

INTRODUCTION

The 82nd Texas State legislators passed three Senate Bills that may create more problems than solutions, accompanied by a plethora of unintended consequences.

There are many reasons for GCD to promulgate rules including:

- Compliance with local, state and federal laws
- Proactive management is always more prudent and cheaper than reactive management
- Carefully crafted rules, Management Plans and Mitigation Plans serve as partial litigation and disgruntled landowner shields that may at least blunt anticipated problems stemming from the newly created state laws passed during the 82nd legislative session and effective as of September 1, 2011

Specifically, these Bills were entitled **SB-332, SB-660** and **SB-737**.

SB-332 was designed use settle the issue of groundwater ownership. The bill specifies that groundwater is owned by the surface owner, unless severed subject to reasonable rules set forth by groundwater districts. The bill was sponsored and pushed by the Farm Bureau, Texas Southwestern Cattle Association and others.

SB-332 creates some geologic issues that were not anticipated by the collective wisdom of the Texas State Legislators. Some of these issues will be outlined below.

For example, let us consider a 100- acre tract under the following conditions and groundwater district rules:

- District designates correlative rights to be 1 acre feet per acre
- Allows the pumping of 100 acre feet per year
  - 100 x 325,851 gallons = 32.585 million gallons per year
  - 89,274 gallons per day
  - 62 gallons per minute

Let's further assume the landowner plans to install an irrigation pivot system on the SW corner of the 100 acre site.

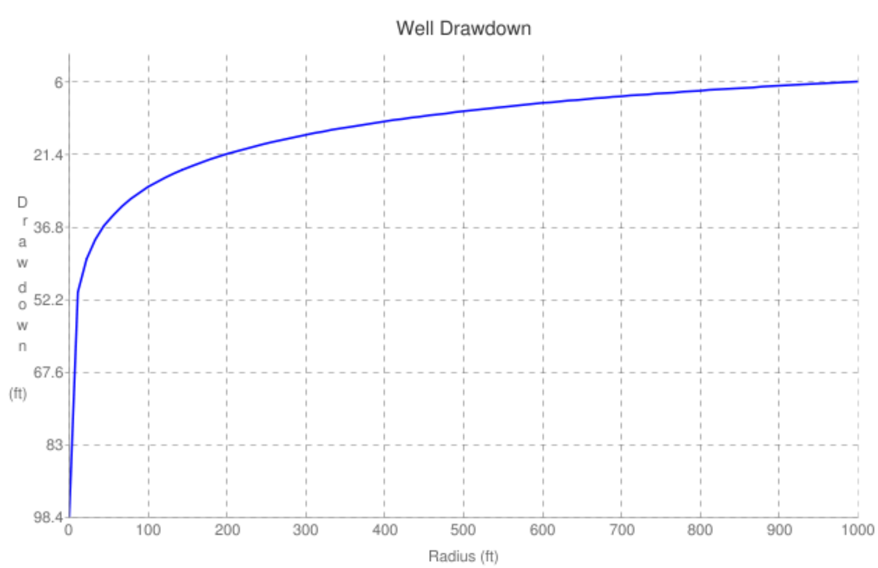
Theis Equation Calculator

Calculation

Radius, (r)	500	Foot
Storage Coefficient, (S)	0.0008	
Transmissivity (T)	1400	GPD/ft
Time (t)	5	Days
Discharge, (Q)	62	GPM
Drawdown, (s)	12.21	Foot

Function Parameters

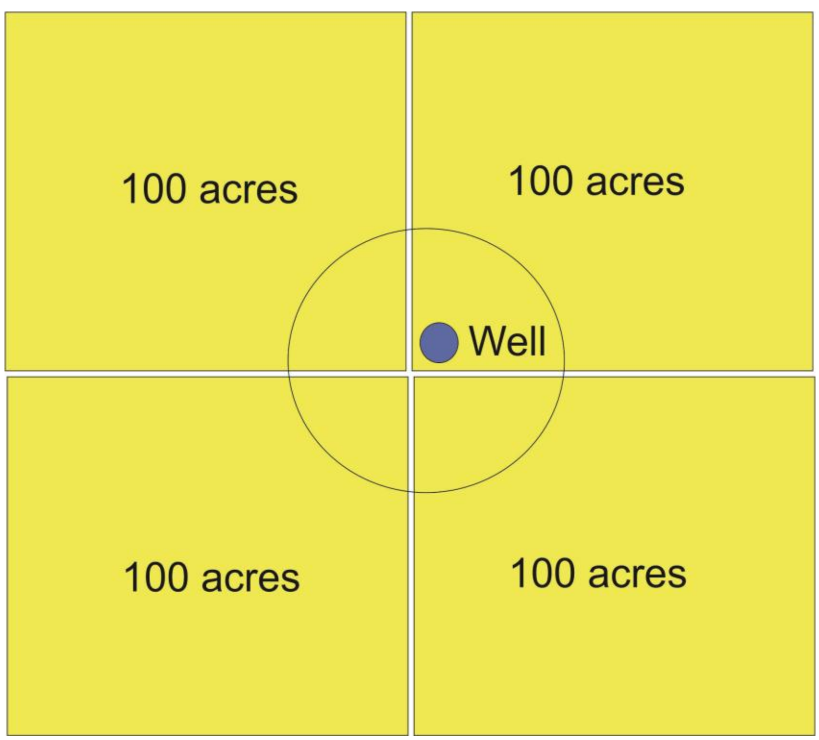
u =1.87* r^2*S/(T*t) for default units	0.053428571428571 43
Well Function, W(u)	2.4049169380412234



It can be easily seen that neighbors that own land within 500 feet of the SW corner of the permitted 100 acres will be losing their ownership of the groundwater beneath their land by at least 12.1 feet per week per acre owned under SB-332. This would amount to an estimated 3.9 million gallons per week.

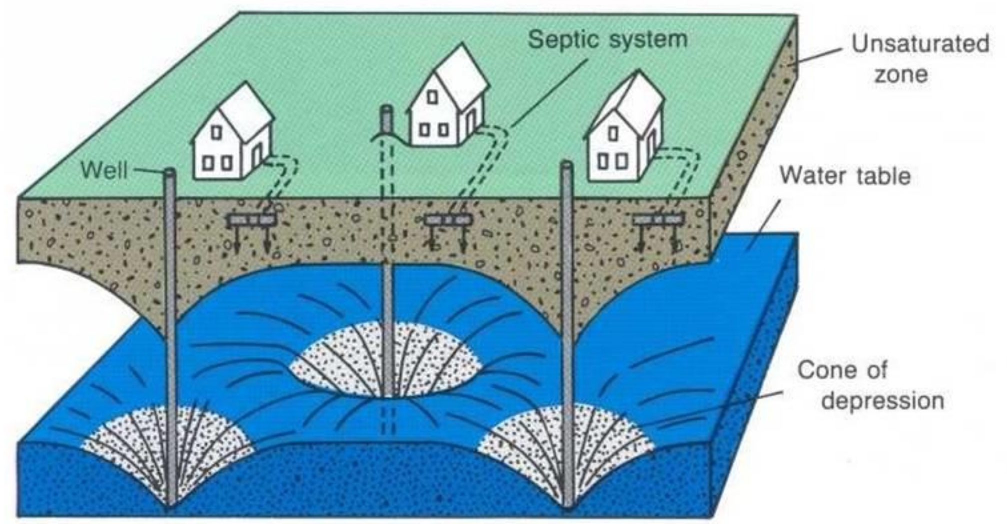
This brings forth some interesting **SB-332** questions:

- What is this “stolen” water worth?
- What is the worth of the damages?
- What would the cumulative drawdown be if the neighbor also owned a 100 acre-foot permit and drilled their well near the neighbor’s SW corner well?
- How could a water district have prevented these problems?
- Could the water district be legally culpable for weak rules?



It is plain this radius of drawdown could impact not just one neighbor, but three neighbors.

It should also be noted that any edge position will impact one or more neighbors.



Potential geologic and district rules might include:

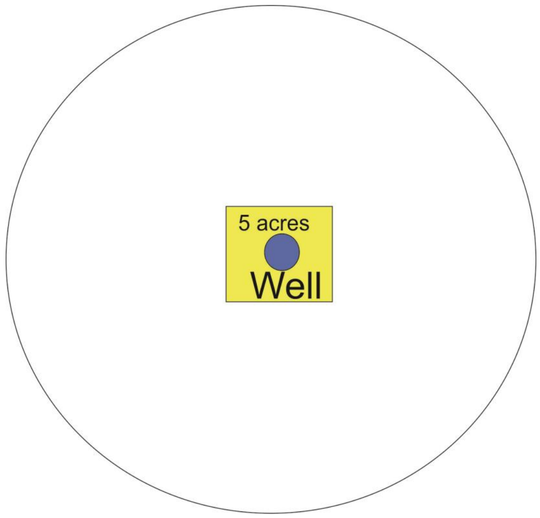
- Central position
- Calculations based upon gallons per minute
- Calculations based upon radius of influence
- Limitations to the doctrine of 1 acre-foot per acre dependent upon well position and pump capabilities

It can readily be seen that correlative rights and **SB-332** may foster a litany of problems for landowners and water districts.

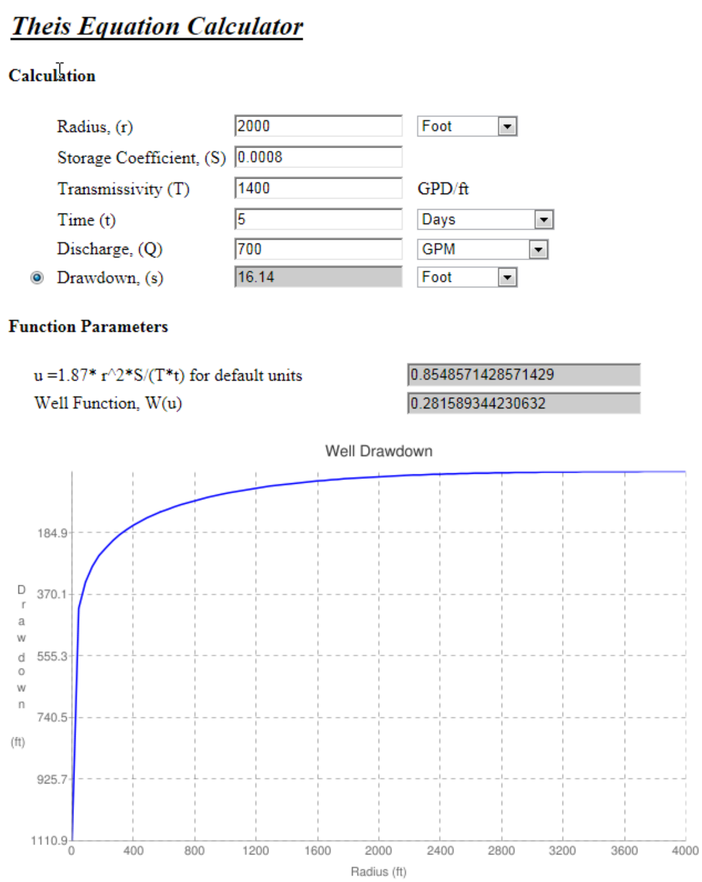
For a second example, let us consider a rural public water system that serves either an incorporated city and/or rural customers.

The following assumptions are as follows:

- PWS water well drilled 5-acre fee
- Pumps 700 gpm, 5 days per week



Radius of influence 2,000 feet beyond the 5-acre fee.



This calculation indicates that the drawdown will be about 16 feet out to 2,000 feet beyond the well.

Five acres covers an area of about 482 x 482 feet. It is clear that many surrounding landowners would have a claim on the withdrawn groundwater unless the PWS either owned or leased the surrounding groundwater property rights under **SB-332**.

This brings forth the similar questions to the irrigation example outlined in the above paragraphs.

These are just a few unintended consequences concerning **SB-332**.

SB-737 lays out the following:

> "(b) Requires the district, in issuing permits, to manage total groundwater production on a long-term basis to achieve an applicable desired future condition and consider:
>
> > (1) the modeled available groundwater determined by the executive administrator of the Texas Water Development Board (executive administrator);
> >
> > (2) the executive administrator's estimate of the current and projected amount of groundwater produced under exemptions granted by district rules and Section 36.117 (Exemptions; Exception; Limitations);
> >
> > (3) the amount of groundwater authorized under permits previously issued by the district;

> (4) a reasonable estimate of the amount of groundwater that is actually produced under permits issued by the district; and
>
> (5) yearly precipitation and production patterns."

The most difficult aspect of **SB-737** is the recharge implications sited under item (5) as shown above. It is also that all permits will be subject to "modeled" available groundwater. Recall that the TWDB budget has been cut by 30% and approximately ½ of their modelers were laid off prompting service cutbacks.

This places more of the burden upon the water districts to defend and promulgate applicable rules to comply with the new laws effective September 1, 2011.

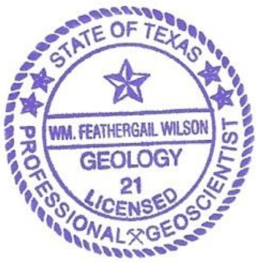
The PCCD must consider these new laws and their unintended consequences as proactive predictions and applicable rules, groundwater management and mitigations plans.

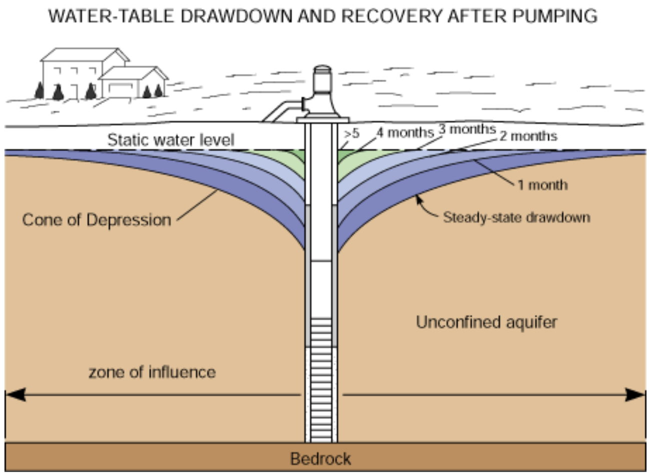
SB-660 is a complex bill concerning measuring, managing and procedures applied to the DFC's. The elements of this bill will have to be incorporated into the Rules, the Management Plan and perhaps a Mitigation Plan.

The bill forces more spending down to the GCD level including:

- Monitoring costs
- Geological services
- Legal services
- Modeling costs
    - Sub-regional level
    - GMA level
    - GCD level

William Feathergail Wilson, PG 21





GEOLOGY OF ASR WELLS

BY

William Feathergail Wilson
Texas PG 21
May, 2012

INTRODUCTION

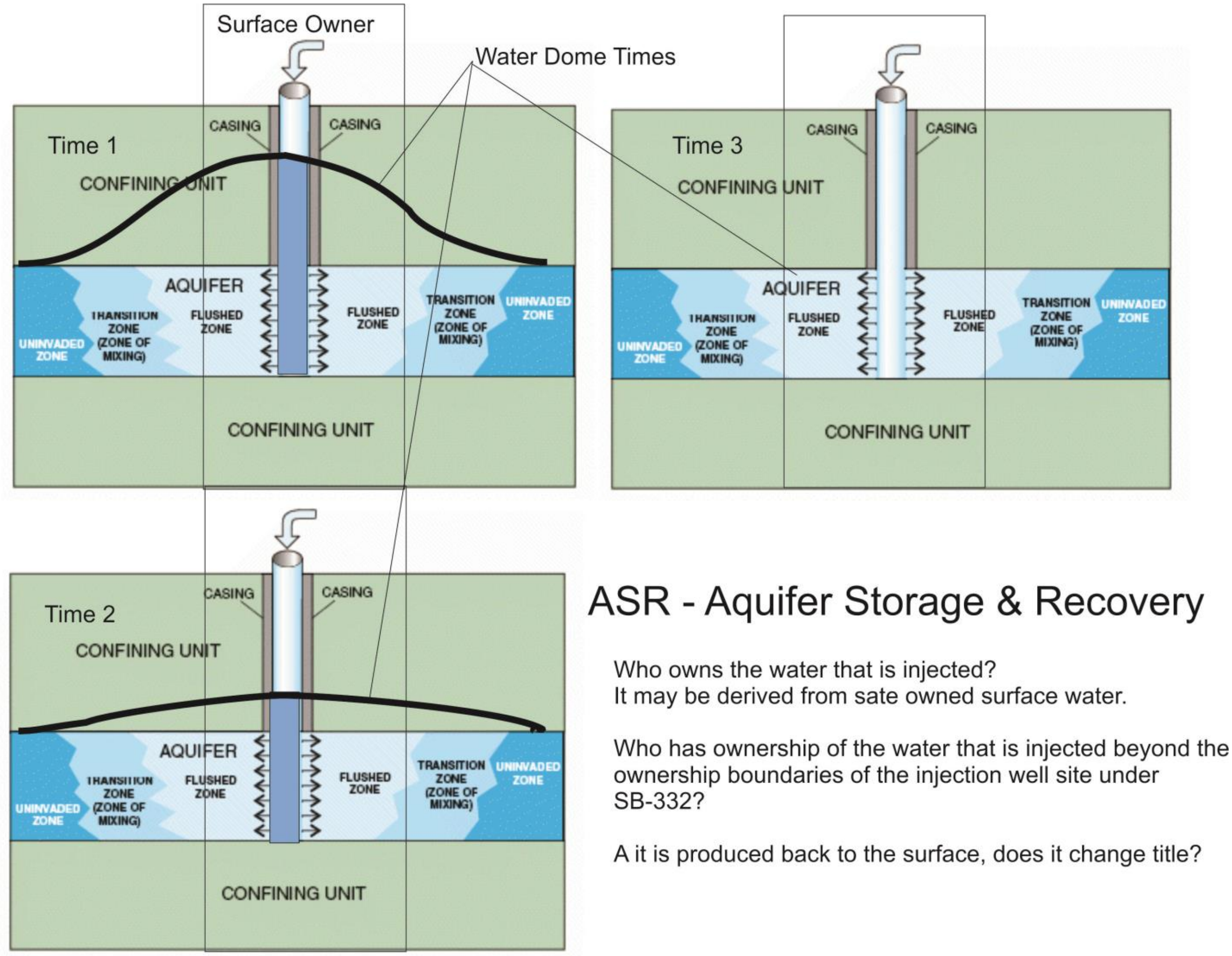
There are many reasons for GCD to promulgate rules including:

- Compliance with local, state and federal laws
- Proactive management is always more prudent and cheaper than reactive management
- Carefully crafted rules, Management Plans and Mitigation Plans serve as partial litigation and disgruntled landowner shields that may at least blunt anticipated problems stemming from the newly created state laws passed during the 82nd legislative session and effective as of September 1, 2011

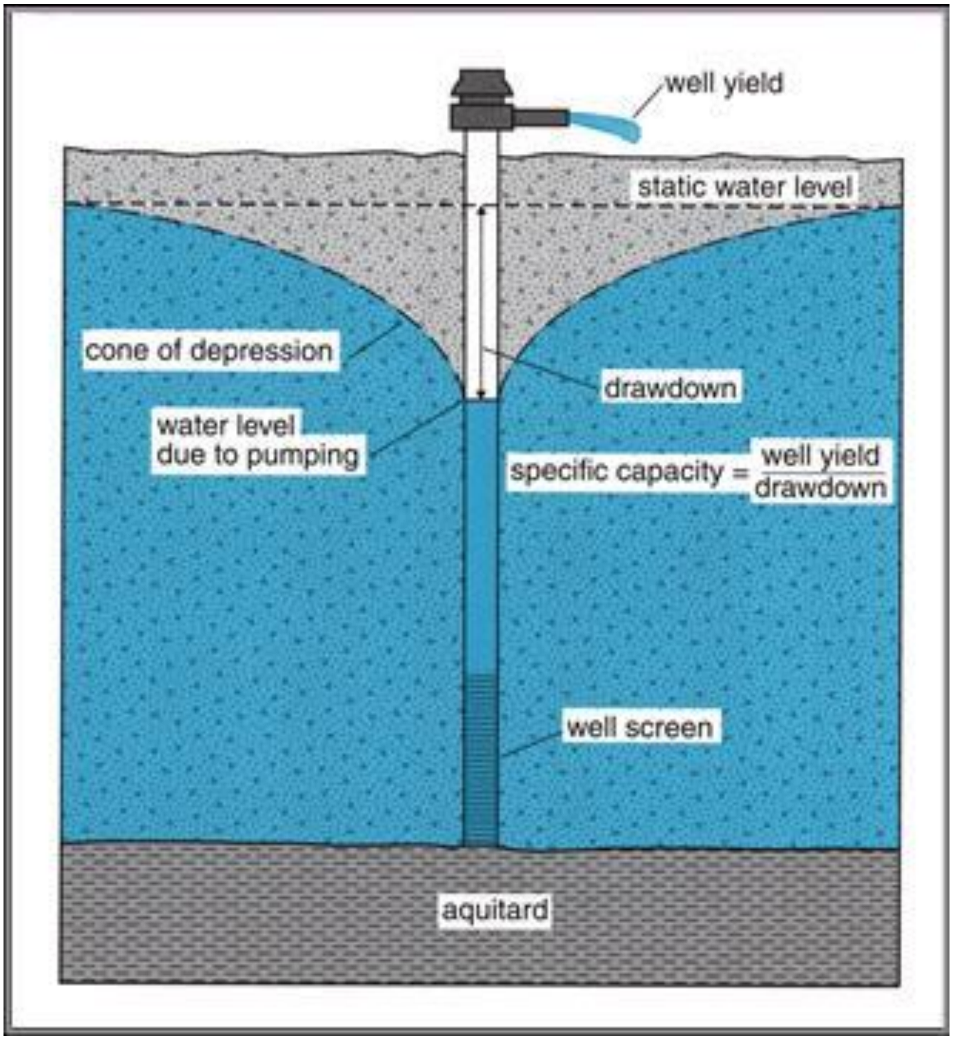
ASR Wells

Aquifer Storage and Recovery wells may pose some very specific problems stemming from SB-332, SB-660 and SB-737.
An ASR well takes surface water generally from a river or a steam and injects into an aquifer to be stored and later retrieved. ASR wells are almost always Public Water Supply Wells. They do require GCD permits to drill and complete as well TCEQ approval.

They are far more expensive than ordinary rural water supply wells and require extensive planning and surface equipment. Most of the ASR wells exceed $1million dollars.



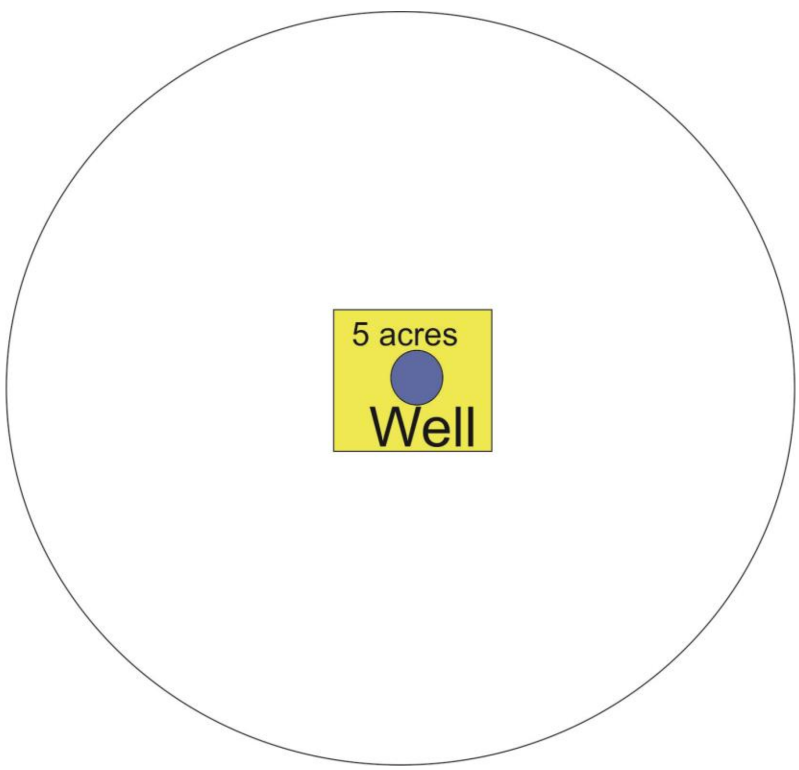
The schematic shown above outlines a few of the problems and unintended consequences that may arise from an ASR well. Note that an ASR wells results in *"cone or hill of water"* above the confining layer subject to the same equations that describe *the "cone of depression"* that govern withdrawal of water.



SB-332 was designed use settle the issue of groundwater ownership. The bill specifies that groundwater is owned by the surface owner, unless severed subject to reasonable rules set forth by groundwater districts. The bill was sponsored and pushed by the Farm Bureau, Texas Southwestern Cattle Association and others.

SB-332 creates some geologic issues that were not anticipated.
For example, let us consider a 5- acre tract with an ASR well drilled outside the city limits or on the edge of the city limits under the following conditions and groundwater district rules:

- The city or the ASR owner may demonstrate they have the surface water rights
- The ASR owner may not inject beyond the radius of influence without owning or leasing the groundwater rights of adjacent landowners
- Questions arise as to owns and controls the groundwater once it crosses ownership boundaries
    - Does the groundwater change title when it crosses a landowner’s boundary under SB-332 ?



Radius of influence 2,000 feet beyond the 5-acre ASR fee.

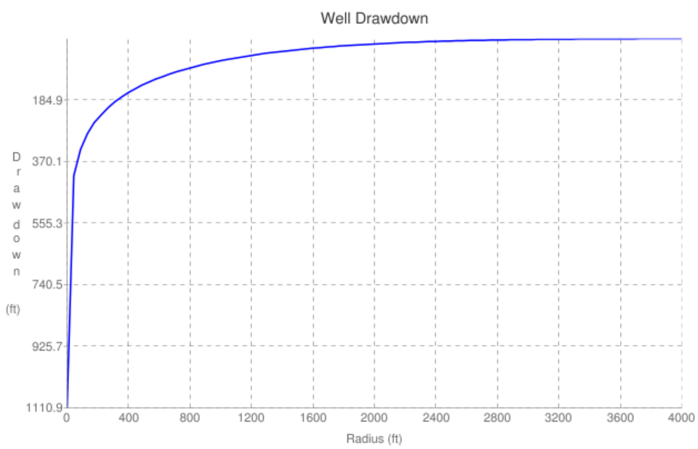
Theis Equation Calculator

Calculation

Radius, (r)	2000	Foot
Storage Coefficient, (S)	0.0008	
Transmissivity (T)	1400	GPD/ft
Time (t)	5	Days
Discharge, (Q)	700	GPM
Drawdown, (s)	16.14	Foot

Function Parameters

u =1.87* r^2*S/(T*t) for default units	0.8548571428571429
Well Function, W(u)	0.281589344230632



This calculation indicates that the drawdown or an ASR *"radius of influence"* will be about 16 feet out to 2,000 feet beyond the well.

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(5) yearly precipitation and production patterns."

The most difficult aspect of **SB-737** is the recharge implications sited under item (5) as shown above. It is also that all permits will be subject to "modeled" available groundwater. Recall that the TWDB budget has been cut by 30% and approximately ½ of their modelers were laid off prompting service cutbacks.

This places more of the burden upon the water districts to defend and promulgate applicable rules to comply with the new laws effective September 1, 2011.

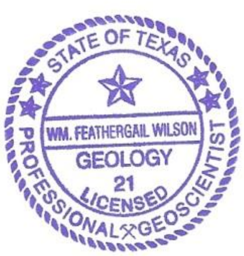
The PCCD must consider these new laws and their unintended consequences as proactive predictions and applicable rules, groundwater management and mitigations plans.

SB-660 is a complex bill concerning measuring, managing and procedures applied to the DFC's. The elements of this bill will have to be incorporated into the Rules, the Management Plan and perhaps a Mitigation Plan.

The bill forces more spending down to the GCD level including:

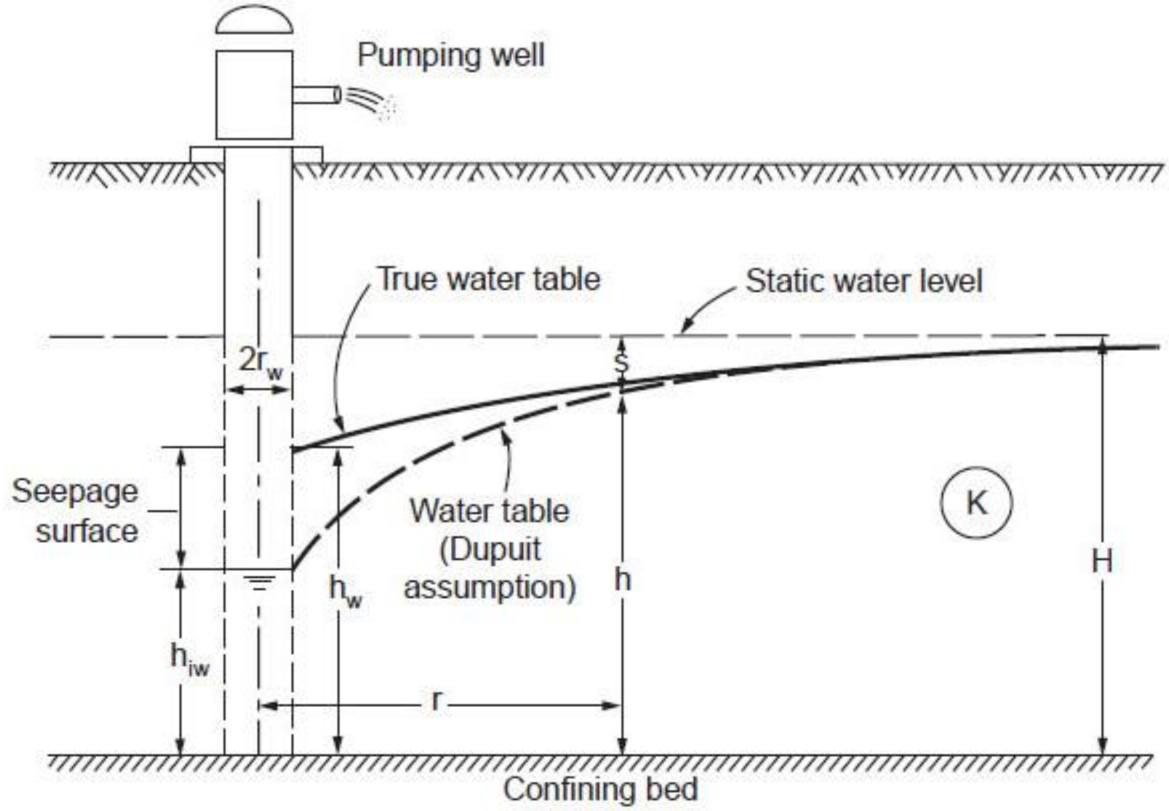
- Monitoring costs
- Geological services
- Legal services
- Modeling costs
    - Sub-regional level
    - GMA level
    - GCD level

All of these new bills will require considerable time and effort, as well as careful study.



Theis Equation Calculator

http://www.icalcul8.com/theis.php



$$u_a = r^2 S/(4Tt)$$

$$W(u) = -0.577216 - \ln u + u - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} - \cdots$$

$$s(r,t) = [Q/(4\pi T)] \int_u^\infty (e^{-z}/z)\,dz = [Q/(4\pi T)]\,W(u)$$

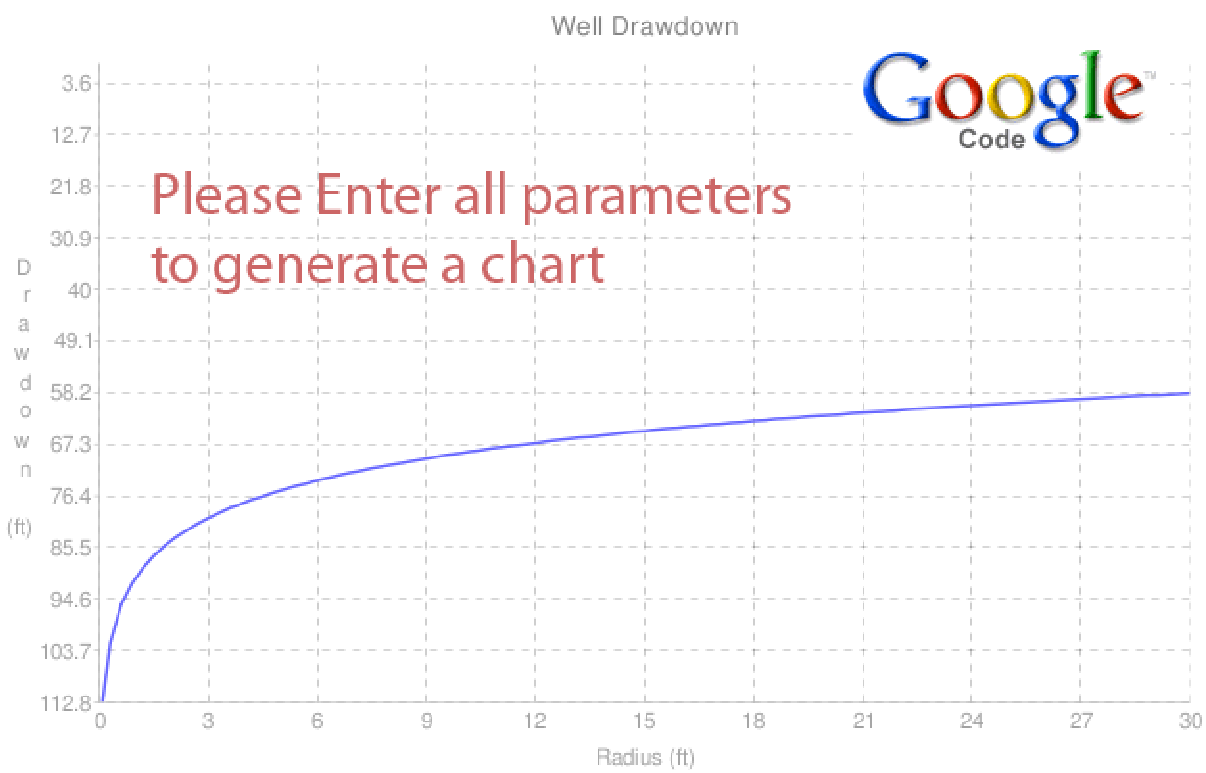
Theis Equation Calculator

Calculation

Radius, (r)		Foot
Storage Coefficient, (S)		
Transmissivity (T)		GPD/ft
Time (t)		Days
Discharge, (Q)		GPM
◉ Drawdown, (s)	NaN	Foot

Function Parameters

u =1.87* r^2*S/(T*t) for default units	NaN
Well Function, W(u)	NaN



DIFFERENCE BETWEEN K & T

BY

William Feathergail Wilson
Texas PG 21
May, 2012

INTRODUCTION

There are three fundamental groundwater numbers derived from pump tests.

1. Storage Coefficient (Sc)
2. Hydraulic Conductivity (K)
3. Transmissivity (T)

The following 2010 North Carolina Division of Natural Resources paper describes these concepts.

Basic Hydrogeology

GROUND WATER, AQUIFERS & CONFINING BEDS

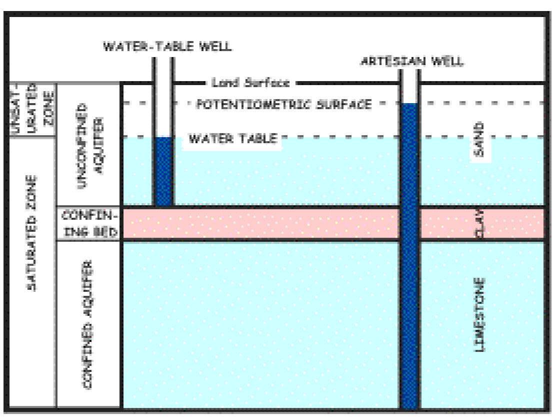
Aquifer - "A water-bearing layer of rock, or of unconsolidated sediments, that will yield water in a usable quantity to a well or spring."

Confining Bed - "A layer of rock, or of unconsolidated sediments, that retards the movement of water in and out of an aquifer and possesses a very low hydraulic conductivity."

From these definitions, all rocks can be thought of as either aquifers or confining beds. Moreover, aquifers are often considered to be *unconfined* or *confined.*

An aquifer is considered unconfined if water only partially fills the aquifer materials and water freely rises and declines along the unsaturated/saturated zone boundary. These unconfined aquifers are often referred to as water-table aquifers and wells that are opened to these unconfined aquifers indicates the position of the water-table.

A confined aquifer is generally defined when water completely fills the aquifer materials and is overlain by a confining bed. A common term for a confined aquifer is an artesian aquifer. The water level from a well that permits water solely from a confined aquifer to enter the well will stand at some point above the top of the confined aquifer but not necessarily above the land surface. The water level in a well open to a specific confined aquifer stands at the level of the potentiometric surface. If the potentiometric surface is above land, the well is often considered as a free-flowing artesian well.



Reference: modified from Heath (1993)

POROSITY, SPECIFIC YIELD & SPECIFIC RETENTION

Our understanding of porosity provides us the ability to quantify the volume of water contained in our aquifers. Porosity is best understood as the ratio of the voids to the total volume of an unconsolidated or consolidated material.

$$n = \frac{V_t - V_s}{V_t} = \frac{V_v}{V_t}$$

Note: n = porosity as a decimal fraction
Vt = the total volume of a material
Vs = the volume of the solids in the material
Vv = the volume of the voids

Often, porosity is expressed as a percentage by multiplying the ratio by 100. Porosity also depends on the range of grain size (sorting) and shape of the subject material, but not on the size. Fine-grained materials tend to be better sorted than coarse-grained materials, thereby exhibiting greater porosities.

SELECTED VALUES OF POROSITY		
Grain Size	Material	Porosity (%)
Fine	Clay	50
↕	Sand	25
Coarse	Gravel	20

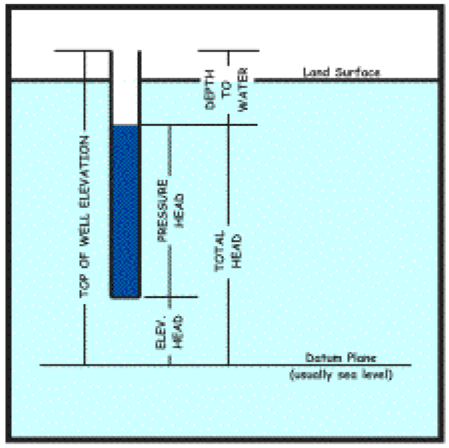
By looking at the above table one might conclude that fine-grained materials have the greatest ability to supply water to a well. This is not the case because physical properties such as adhesion (the molecular attraction of two different substances) and cohesion (the molecular attraction of similar substances) limit an aquifer's ability to release water into a well. Water stored in an aquifer that is retained as a film on the aquifer material or in very small openings is called specific retention. Conversely, water stored in an aquifer that will drain under the influence of gravity is called specific yield. The term effective porosity is often used to describe specific yield. With concepts of specific yield and retention in mind, let's look at our porosity chart once again.

SELECTED VALUES OF POROSITY, SPECIFIC YIELD(%) & RETENTION(%)				
Grain Size	Material	Porosity (%)	Specific Yield	Specific Retention
Fine	Clay	50	2	48
↕	Sand	25	22	3
Coarse	Gravel	20	19	1

As we can conclude, finer-grained materials such as clay have a high porosity but also have a high specific retention and low specific yield when compared to their coarse-grained counterparts, thereby limiting its ability to provide water to a well.

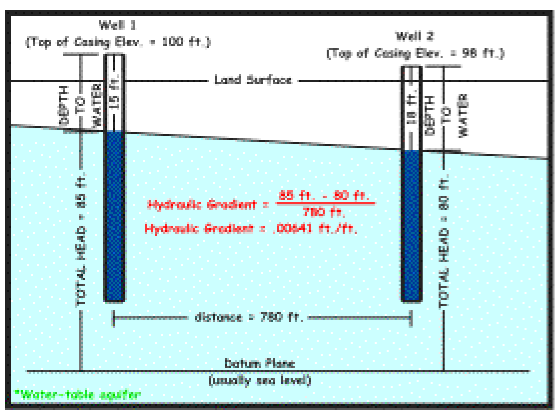
HYDRAULIC HEAD & GRADIENTS

As previously discussed, water entering an unconfined or confined well will stand at a particular level. This level is often termed as the ***hydraulic head*** and is actually the sum of three components - the pressure head, elevation head and velocity head. The velocity head is often disregarded because ground water movement in most cases is relatively slow. In practical applications, a depth to ground water measurement is obtained and subtracted from the top of the well casing elevation to measure total head. Note that the datum plane illustrated below is often calibrated to sea level.



When ground water level measurements are collected for a specific aquifer and contoured in a map perspective, a ground water surface map can be generated. Remember, water level measurements obtained from an unconfined aquifer represents the water table surface, and represent the potentiometric surface for water levels obtained from a confined aquifer.

The direction of ground water movement can be understood in the fact that ground water ***always*** flows in the direction of decreasing head. The rate of movement on the other hand is dependent on the ***hydraulic gradient***, which is the change in head per unit distance. The change in head measurement is ideally in the direction where the maximum difference of head decrease occurs. In the example below, the hydraulic gradient is determined to be .00641 ft./ft. (the change in head divided by the change in distance). Notice the units are foot by foot but can be described in more inconsistent units such as foot per mile.



Reference: modified from Heath (1993)

The direction and hydraulic gradient can be determined if the following data are available for three wells located in a triangular pattern.

(1) Relative geographic position of the wells.
(2) Distance between wells.

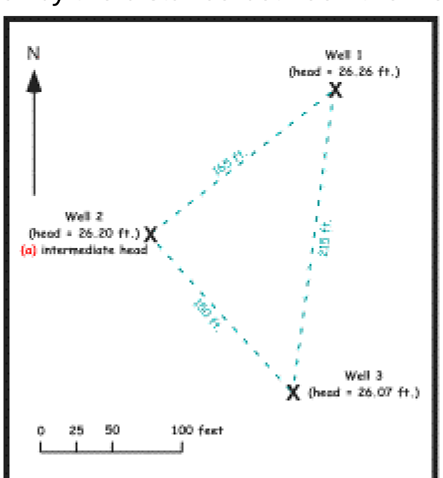
(3) Total head (ground water level) at each well.

The solution is outlined and illustrated below.
(a) Identify the well that has the intermediate water level.
(b) Calculate where the elevation of the well with the intermediate head would fall along a straight line between the wells having the highest and lowest heads.
(c) Draw a straight line from the well with the intermediate head to its elevation equivalent plotted along the straight line between the wells having the highest and lowest heads. This line represents a segment of the water-level contour whereby the total head is the same as the intermediate well
(d) Draw a line perpendicular to the water-level contour line just plotted with the well of highest or lowest head. This line is the line that parallels ground water direction.
(e) Now, calculate the difference between the head of the well and that of the intermediate head contour by the distance between the well and the contour to reveal the hydraulic gradient.

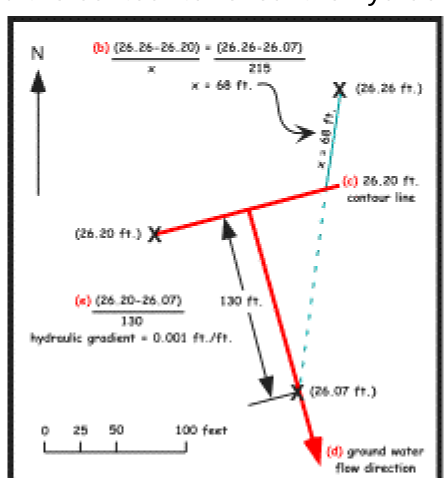
Thus, ground water flow direction is towards the south east at a hydraulic gradient of .00641 ft/ft.

The direction and hydraulic gradient can be determined if the relative geographic position, distance between wells and total head are available for three wells located in a triangular pattern.

The solution is outlined and illustrated below (Heath, 1993).
(a) Identify the well that has the intermediate water level.
(b) Calculate where the elevation of the well with the intermediate head would fall along a straight line between the wells having the highest and lowest heads.
(c) Draw a straight line from the well with the intermediate head to its elevation equivalent plotted along the straight line between the wells having the highest and lowest heads. This line represents a segment of the water-level contour whereby the total head is the same as the intermediate well
(d) Draw a line perpendicular to the water-level contour line just plotted with the well of highest or lowest head. This line is the line that parallels ground water direction.
(e) Now, calculate the difference between the head of the well and that of the intermediate head contour by the distance between the well and the contour to reveal the hydraulic gradient.



(1)



(2)

Thus, ground water flow direction is towards the southeast at a hydraulic gradient of 0.001 ft/ft.

DARCY'S LAW & HYDRAULIC CONDUCTIVITY (K)

In the mid-1800s the French engineer Henry Darcy successfully quantified several factors controlling ground water movement. These factors are expressed in an equation that is commonly known as Darcy's Law.

$$Q = KA\left(\frac{dh}{dl}\right)$$

Note: Q = discharge (volume of water per unit time)
K = hydraulic conductivity (dependent upon size and arrangement of pores, and fluid dynamics such as viscosity, density and gravitational effects)
A = cross-sectional area (at a right angle to ground water flow direction)
dh/dl = hydraulic gradient (this is the common notation for a change in head per unit distance)

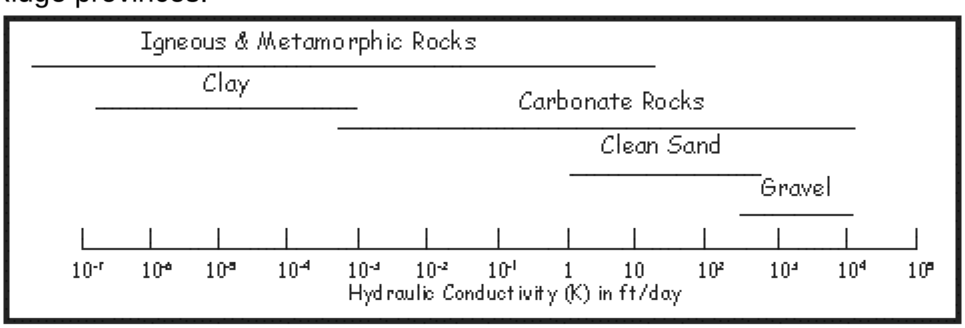
By rearranging Darcy's Law and solving for hydraulic conductivity (K) in common units we can get a sense of what hydraulic conductivity really represents.

$$K = \frac{Qdl}{Adh} \quad \text{or,} \quad K = \frac{Q = \text{volume in ft}^3 \text{ per time (day)}}{A = \text{a cross-sectional area in ft}^2}\left(\frac{dl = \text{distance in ft}}{dh = \text{head change in ft}}\right)$$

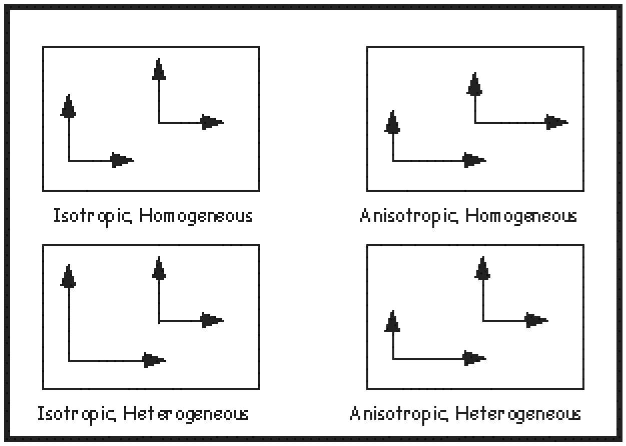
Thus, in practical terms hydraulic conductivity is the volume of water flowing through a 1 ft. x 1 ft. cross-sectional area of an aquifer under a hydraulic gradient of 1 ft./ 1 ft. in a given amount of time (usually a day). If we cancel out our units, we see that hydraulic conductivity is usually expressed in ft./day.

$$K = \frac{\cancel{ft^3}/day}{\cancel{ft^2}}\left(\frac{\cancel{ft}}{\cancel{ft}}\right) = ft/day$$

Hydraulic conductivity ranges approximately 12 orders of magnitude depending upon differing water transmitting characteristics of aquifer materials. As one may conclude from the chart below, the volume of water that can flow from our sandy and cavernous carbonate aquifer materials of the coastal plain are in most cases far greater than our rocks within the Piedmont and Blue Ridge provinces.



There are also some other terms used when regarding the spatial distribution of hydraulic conductivity within an aquifer. If the value of hydraulic conductivity is the same in all directions, the aquifer is said to be isotropic. If hydraulic conductivity is different in different directions, the aquifer is said to be anisotropic. The terms homogeneous and heterogeneous are used when comparing hydraulic conductivity at separate locations of the aquifer, regardless whether the value is the same or different in all directions. The aquifer is homogeneous if hydraulic conductivity is the same and heterogeneous if different. The diagram below shows the four possible combinations when describing the hydraulic conductivity of aquifers.



Another important factor controlling ground water movement is its velocity. The ground water velocity equation can be derived from a combination of the velocity equation of hydraulics and our familiar friend, Darcy's Law.

$$Q = Av$$

velocity equation

$$Q = KA\left(\frac{dh}{dl}\right)$$

Darcy's Law

Note: Q = discharge (volume of water per unit time)
K = hydraulic conductivity
A = cross-sectional area (at a right angle to ground water flow direction)
dh/dl = hydraulic gradient
v = velocity

We can solve for ground water velocity by; 1. substituting discharge (Q) by the cross-sectional area at a right angle to flow direction (A) times velocity (v) and, 2. cancelling our units. When we do this we discover that velocity (v) is equal to hydraulic conductivity (K) times hydraulic gradient (dh/dl).

$$Av = KA\left(\frac{dh}{dl}\right)$$

Step 1

$$\cancel{A}v = K\cancel{A}\left(\frac{dh}{dl}\right) \longrightarrow v = K\left(\frac{dh}{dl}\right)$$

Step 2

In practical terms we know that ground water does not move in open space, rather it moves through aquifer materials that impedes ground water velocity. To account for this we need to include effective porosity (specific yield) to accurately quantify ground water velocity. Remember, hydrogeologists use effective porosity because this value better represents water flowing through an aquifer under the forces of gravity. Thus the velocity equation is modified.

$$v = \left(\frac{Kdh}{n_e dl}\right)$$

The ground water velocity equation
(n_e is effective porosity)

Let's take a look at the difference of ground water velocity when comparing characteristics of a sandy substrate to that of a clay substrate. As we can see, ground water tends to move quicker in materials with higher hydraulic conductivities (those materials also have higher effective porosities).

1. Sandy material.

K = 50 ft/day

dh/dl = 1 ft/1000 ft

n_e = 0.22

$$v = \frac{K}{n_e} \times \frac{dh}{dl}$$

$$v = \frac{50\text{ft}}{\text{day}} \times \frac{1}{0.22} \times \frac{1\text{ ft}}{1000\text{ ft}}$$

v = 0.227 ft/day

2. Clayey material.

K = 0.00001 ft/day

dh/dl = 1 ft/100 ft

n_e = 0.02

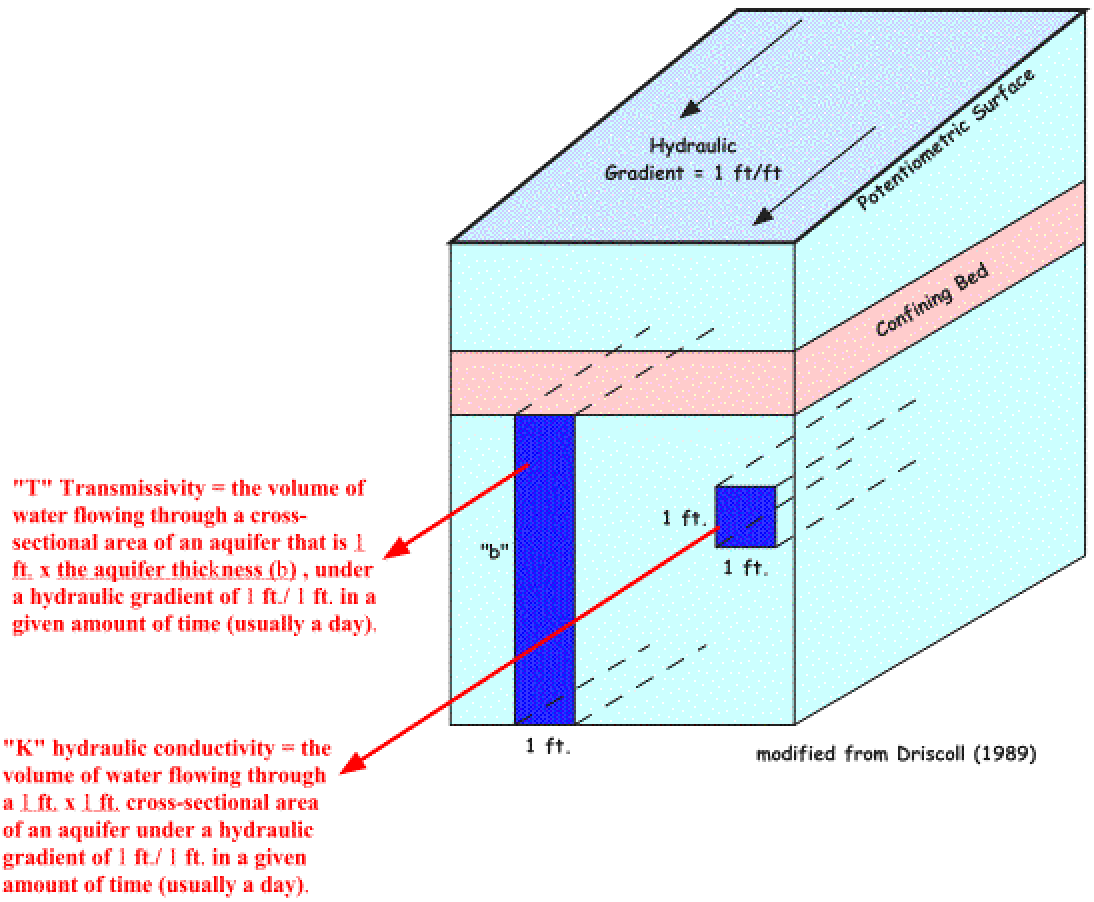
$$v = \frac{K}{n_e} \times \frac{dh}{dl}$$

$$v = \frac{0.00001\text{ft}}{\text{day}} \times \frac{1}{0.02} \times \frac{1\text{ ft}}{100\text{ ft}}$$

v = 0.000005 ft/day

TRANSMISSIVITY (T)

Transmissivity (T) is the volume of water flowing through a cross-sectional area of an aquifer that is 1 ft. x the aquifer thickness (b), under a hydraulic gradient of 1 ft./ 1 ft. in a given amount of time (usually a day). If we think about our definition of hydraulic conductivity, we can conclude that transmissivity (T) is actually equal to hydraulic conductivity(K) times aquifer thickness (b). Or otherwise denoted as T = Kb. We can also conclude that transmissivity is expressed as ft2/day because if T = Kb, then T = (ft./day)(ft./1). It is difficult to understand the differences between "T" and "K" when first introduced to these terms - the illustration below should hopefully bring it all together.



The differences in transmissivities in our coastal plain vary greatly. Some of our Cretaceous age aquifers have transmissivites that are low as 100 to 1,000 ft2/day. Conversely, transmissivity in the Eocene age Castle Hayne Limestone can be as high as 50,000 ft2/day!!!

STORAGE COEFFICIENT (S)

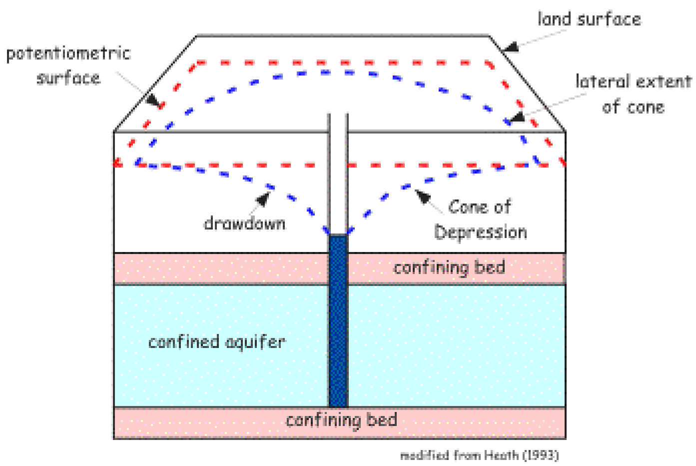
You'll often hear hydrogeologists speak of the "T" and "S" of aquifers. We now have an understanding of "T" or transmissivity. The "S" is used to represent the storage coefficient of an aquifer which is the volume of water released from an aquifer per 1 foot surface area per 1 foot change in head. Notice that we are not speaking of water flowing through an aquifer, rather we are referring an aquifer's ability to store water. Mathematically, the storage coefficient is dimensionless as the equation below illustrates.

$$S = \frac{Q = \text{volume of water in } ft^3}{(\text{surface area in } ft^2)(\text{head change in } ft)} = \frac{\cancel{ft^3}}{\cancel{ft^3}}$$

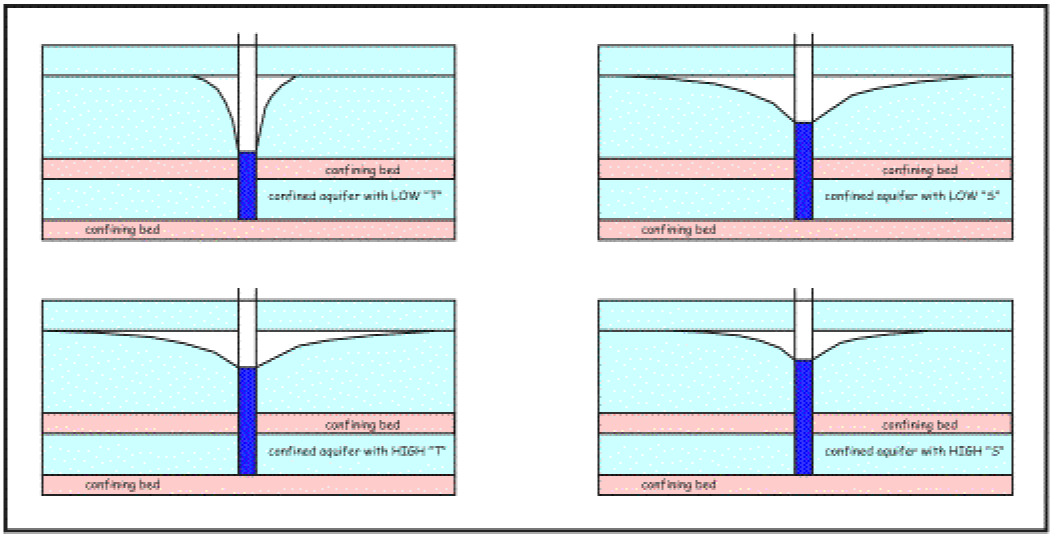
The size of the storage coefficient is dependent whether the aquifer is unconfined or confined. In regards to a confined aquifer, water derived from storage is relative to; (1) the expansion of water as the aquifer is depressurized (pumped) and, (2) compression of the aquifer. In a confined aquifer setting, the load on top of an aquifer is supported by the solid rock skeleton and the hydraulic pressure exerted by water (the hydraulic pressure acts as a support mechanism). Because of these variables, the storage coefficient of most confined aquifers range from 10-5 to 10-3 (0.00001 to 0.001). Conversely, in an unconfined aquifer setting, the predominant source of water is from gravity drainage and the expansion of water and compaction of the rock skeleton is negligible. Thus, the storage coefficient is approximate to value of specific yield and ranges from 0.1 to about 0.3.

CONES OF DEPRESSION

As water is withdrawn from a well, the water level in the well begins to decline as water is removed from storage in the well. The head in the well will fall below the level of the surrounding aquifer and water begins moving from the aquifer into the well. The water level will continue to decline and the flow rate of water into the well will increase until the inflow rate is equal to withdrawal rate. Water from the aquifer must converge on the well from all directions and the hydraulic gradient must get steeper near the well. For this reason the resultant 3-D shape of water withdrawal is a called a cone of depression.

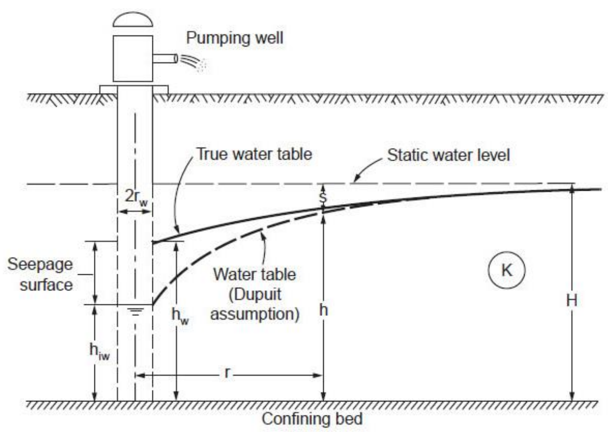


The aquifer parameters of transmissivity (T) and storage coefficient (S) are variables that can dictate the shape of the cone of depression. Relative to a confined aquifer, the expansion of water in response to depressurizing (pumping) is very small, yet compression of the rock skeleton is great. This permits the cone of depression to expand and deepen rapidly when pumped. Thus, lower "S" values create deeper and wider cones than higher "S" value aquifers that do not deepen and expand as readily. In regards to transmissivity, aquifers of low "T" develop deep and narrow cones of depression and aquifers of high "T" area characterized by shallow and wide cones. The reasons for this are fairly complex and require more background information to be explained fully. However, think about the "T" relationship this way - a greater decline in hydraulic head would be required to move water through a less transmissive aquifer than a more transmissive aquifer.



modified from Freeze and Cherry (1979)

The application of Transmissivity to drawdown and thereby the radius of influence becomes a very important issue in permitting and groundwater ownership beneath land parcels.



$$u_a = r^2 S/(4Tt)$$

$$W(u) = -0.577216 - \ln u + u - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} - \cdots$$

$$s(r,t) = [Q/(4\pi T)] \int_u^\infty (e^{-z}/z)\,dz = [Q/(4\pi T)] W(u)$$

The table below taken from Freeze & Cherry text depicts the ranges of transmissivity.

Table 2.2 Range of Values of Hydraulic Conductivity and Permeability

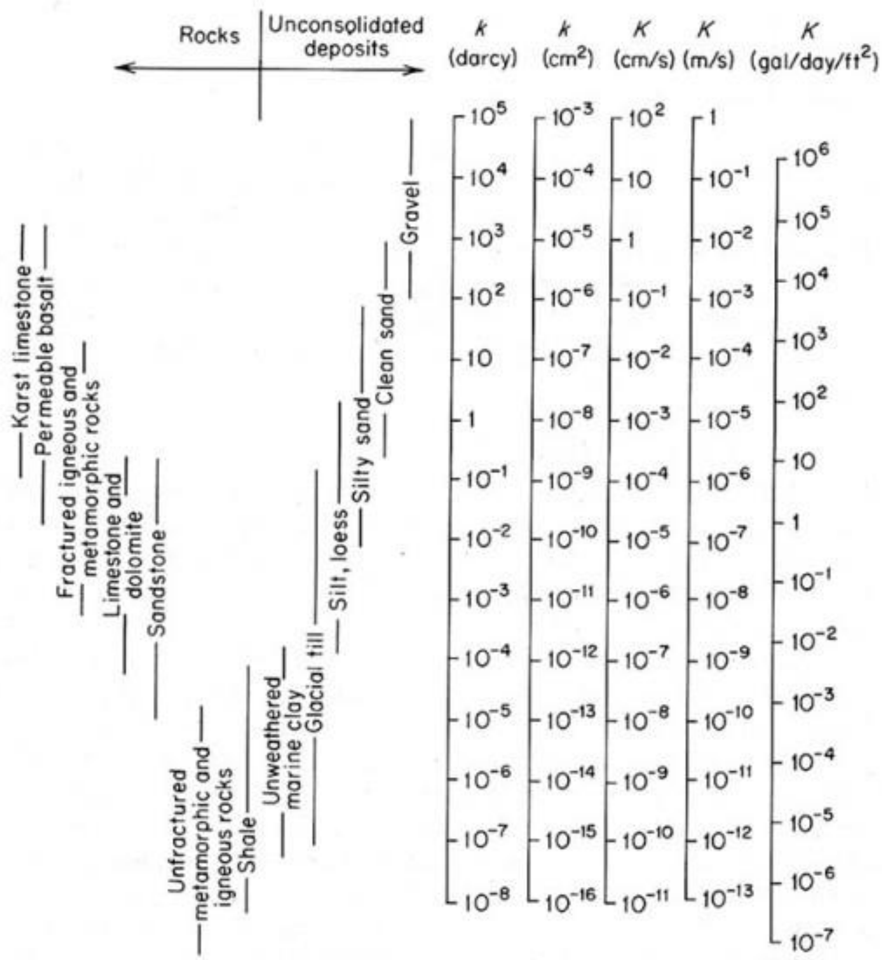


Table 2.3 Conversion Factors for Permeability and Hydraulic Conductivity Units

	Permeability, k*			Hydraulic conductivity, K		
	cm^2	ft^2	darcy	m/s	ft/s	U.S. gal/day/ft²
cm^2	1	1.08×10^{-3}	1.01×10^{8}	9.80×10^{2}	3.22×10^{3}	1.85×10^{9}
ft^2	9.29×10^{2}	1	9.42×10^{10}	9.11×10^{5}	2.99×10^{6}	1.71×10^{12}
darcy	9.87×10^{-9}	1.06×10^{-11}	1	9.66×10^{-6}	3.17×10^{-5}	1.82×10^{1}
m/s	1.02×10^{-3}	1.10×10^{-6}	1.04×10^{5}	1	3.28	2.12×10^{6}
ft/s	3.11×10^{-4}	3.35×10^{-7}	3.15×10^{4}	3.05×10^{-1}	1	6.46×10^{5}
U.S. gal/day/ft²	5.42×10^{-10}	5.83×10^{-13}	5.49×10^{-2}	4.72×10^{-7}	1.55×10^{-6}	1

*To obtain k in ft^2, multiply k in cm^2 by 1.08×10^{-3}.

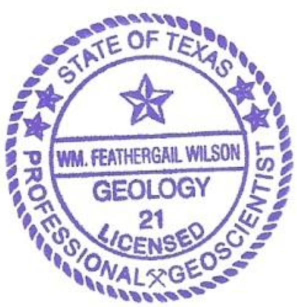
Utilizing this table of K values based upon lithology, T can be estimated by:

$$T = K \text{ x thickness of saturated aquifer}$$

For example, the Reklaw is a silty sand, while the Carrizo is a clean sand. The Wilcox falls mainly within the lower end of the silty sand range, but it is far thicker than the Reklaw.

Another contributing factor is the completion depth of the sands penetrated by each individual well.

By applying these concepts, PCCD may be able to better estimate the validity of permit requests with respect to geology and groundwater hydrogeology.



GROUNDWATER MITIGATION

BY

Robert Wilson, Attorney at Law

William Feathergail Wilson, Geologist, Texas PG 21
March, 2012

A Groundwater Mitigation Plan sets forth specific technical and legal procedures designed to mitigate Rule challenges.

LEGAL BASIS

Mitigation shall be implemented by the PCCD between landowners and groundwater right holders via a formal process conducted by _________.
In the case where the PCCD is challenged, mitigation will be conducted by a third party via a formal process conducted by ________.

(Expand –Change-Rewrite)

TECHNICAL BASIS

The challenging party shall be responsible for the cost of the burden of proof such as follows:

- Drilling of at least three observation wells to the same depth as the challenged aquifer
- Utilizing adequate software, hardware and third party impartial consultants to evaluate the validity of the challenge
- Consult PCCD guidance documents to ascertain the nature of the challenge
- Follow the PCCD Rules and the laws of the State of Texas concerning groundwater

Special attention should be paid to the PCCD Guidance Document entitled "Geology of Correlative Rights" prior to challenges by both and/or all parties.