

Hydrogeology of the Troublesome Aquifer in the Greater Pole Creek Basin, Grand County, Colorado

By
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2024

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ISBN-13



979-8334840522

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View of Sheep Mountain across Pole Creek, Grand County, Colorado, September 2014. Photo credit: D Stoughton

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Acknowledgements

Thom Yoder, District Manager, Tabernash Meadows Water and Sanitation (TMWS) – Thom has made available some of the most pertinent information related to the water quality and aquifer assessments in this study. His history with TMWS and detailed knowledge of the deep Troublesome municipal well has opened the door for a much better data-based understanding of the Troublesome Aquifer.

Stephen Ingram, President of Ingram Drilling, Inc – Thanks to Stephen for insightful initial discussions related to drilling issues within the Greater Pole Creek Basin along with the water deliverability impact of the Troublesome Aquifer. After these discussions, Stephen was helpful in reviewing portions of this report and provided his concurrence on the findings.

Lindsay Stoughton – My deepest thanks go to my wife who has been incredibly supportive of my endeavors and understanding the concerns for the environment and communities of Fraser Valley. I am so grateful for her patience and insights.

About the Authors

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A native of Colorado, Dean received BS degree in Mathematics Engineering and MS degree in Geophysical Engineering from Colorado School of Mines. His 40-year career was within the petroleum industry working for major and independent oil and gas companies located in Denver, London, and Houston. He was involved with exploration, appraisal and development programs reaching both US domestic and world-wide international arenas. His responsibilities included quality geoscience oversight of large-scale offshore projects and team integration with other geoscientists and engineers. He also participated in several multi-company applied research programs. Dean and his wife, Lindsay, have maintained a residence in Grand County, Colorado since 2000. After Dean's retirement in 2015, both are involved with Colorado School of Mines through supporting students through academic and athletic endeavors. They are avid readers and enjoy the great outdoor activities that the mountain environment offers.

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Don is an affiliate professor at Colorado School of Mines. He spent 40 years with the U.S. Geological Survey as a research hydrologist, reducing uncertainties of water budgets of lakes and wetlands with an emphasis on exchanges between groundwater and surface water. Expanding into fluvial settings, Don developed and improved tools and methods for quantifying fluxes across the sediment-water interface, leading to improved understanding of processes that control those exchanges. He holds a BS in geology and geography from Bemidji State University, a MS in hydrogeology from University of Minnesota, and a PhD in fluvial geomorphology from University of Colorado. Don resides part time just north of the Pole Creek drainage and has spent decades exploring the many area trails via bike, foot, and skis.

Abstract

The Troublesome Aquifer is the sole source of water for domestic use in the Greater Pole Creek Basin, situated in the northwestern portion of the upper Fraser River Valley in Grand County, Colorado. Data from drilling records for wells installed near and within recent home developments, municipal water-suppliers, water-quality records, and published reports are summarized as an initial synthesis of aquifer water quantity and quality. Despite persistent drought and increased domestic aquifer-water usage, aquifer-water storage remains robust with water levels little changed during the past 25 years. Water-quality data indicates substantial variability with depth beneath the water table. Prior to deeper drilling for recent residential development, most groundwater in the central portion of the valley was produced from the shallow Alluvial Aquifer. Data from wells completed in the Alluvial Aquifer are also presented for comparison. This document constitutes a new baseline for assessment of current and future groundwater resources within this portion of the Fraser Valley. Suggested future investigations include water-table monitoring and comprehensive water-quality surveys for water derived from wells completed in the Troublesome Aquifer.

1 - Introduction

Climate change is altering the amount and seasonal distribution of precipitation in many parts of the world, which can have a substantial effect on groundwater recharge (Markovich, and others, 2019, p 8295). In places that rely on groundwater to supply municipal and domestic water, accounting for changes in aquifer storage, supply and quality is particularly important (Green and others, 2011). The Fraser Valley, in north-central Colorado, is typical of many inter-mountain valleys in the western USA perceived to be amply supplied by both surface water and groundwater derived from within its watershed (**Fig 1-1a**). Given the episodic and seasonal variability of streamflow, groundwater is the source for most municipal and domestic water systems.

Substantial development continues to occur in the Fraser Valley, creating growing demands for potable water. Persistent drought during the past 25 years has led to concerns that aquifer supplies may be substantially reduced, and that continuing drought may result in insufficient water availability in the future. Therefore, the need exists to assess aquifer storage, changes in water availability over time, and the ability for wells to access and deliver water.

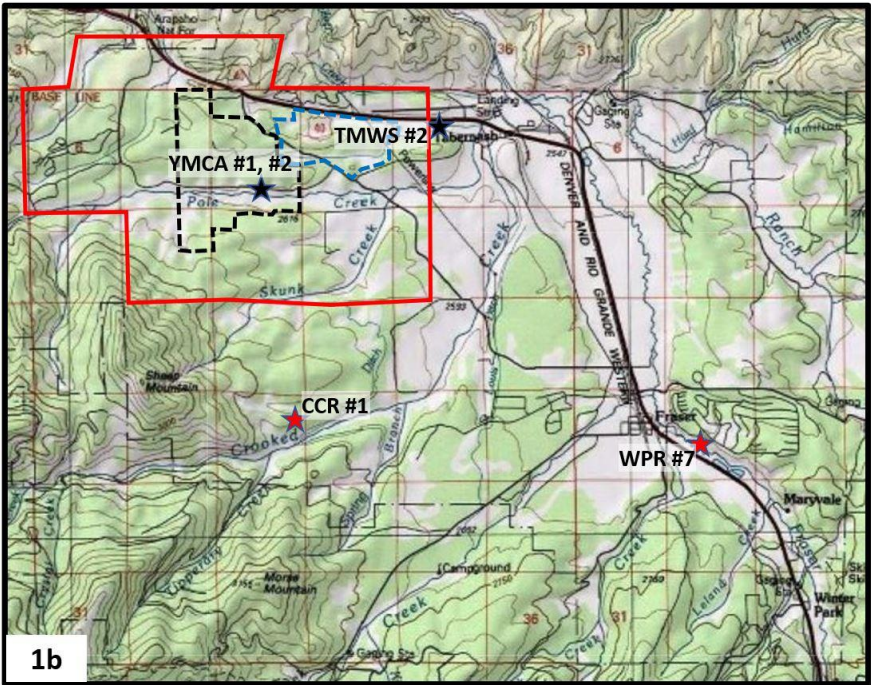
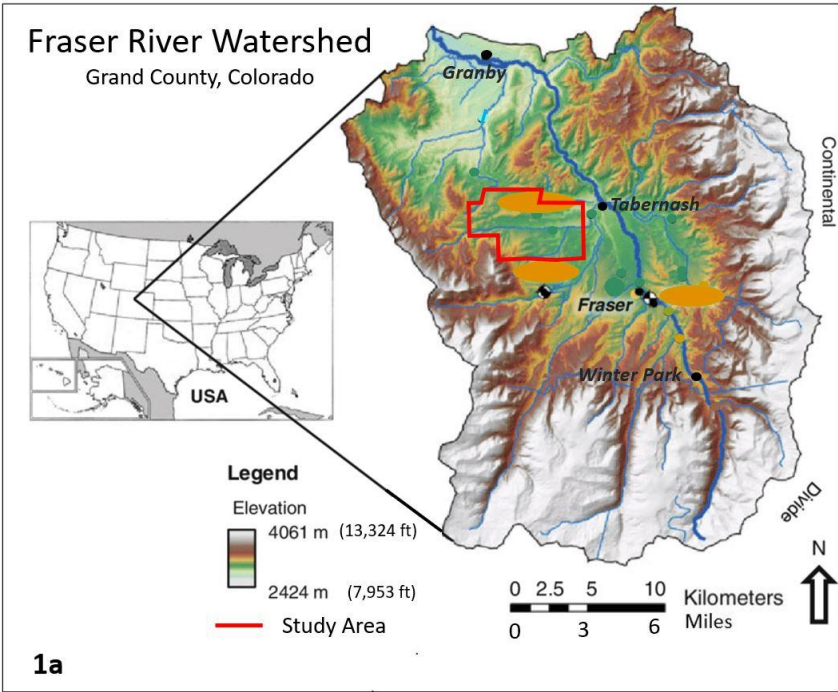
Previous groundwater investigations within the Fraser Valley have been associated with the shallow and relatively thin Alluvial Aquifer within the central portion of the basin (Apodaca and Bails, 1999; Apodaca, Smith, Bails, 2000; Bauch and Bails, 2004; US Army Corp of Engineers, 2014). This aquifer has adequately served the water needs for the majority of domestic and municipal needs. Within the last 25 years, substantial residential population growth has occurred along the flanks of the valley and homeowners have drilled domestic wells to access groundwater from another aquifer, namely the Troublesome Aquifer. This aquifer has substantially different hydraulic properties than the Alluvial Aquifer. Two recently (ca. 2000) constructed communities, The Fairways at Pole Creek and Pole Creek Meadows, are located within the Greater Pole Creek drainage (**Fig 1-1b**) and are the largest of numerous residential developments in the study area. These developments and others in the study area have undergone substantial growth in numbers of single-family residences and domestic water-supply wells. The Troublesome Aquifer that supplies groundwater to meet this growing water demand has been studied little and potential changes in aquifer storage are largely unknown.

1.1 - Purpose and Scope

A literature search is needed to provide a first estimate of the extent and geological characterization of the Troublesome Aquifer and volume of potable water stored in this aquifer. The numbers and locations of domestic, municipal and irrigation wells are summarized to assess the current (2022) collective consumption of water from the aquifer.

Water levels in accessible wells are summarized to create a water-table map of the aquifer. Aquifer hydraulic properties are summarized, and aquifer recharge is estimated, allowing determination of the current aquifer water balance. Future aquifer groundwater supply relative to demand is also projected.

An initial assessment of several water-quality parameters is based on available data. Water chemistry is also related to geochemical parameters, some of which are dependent in part on geophysical logs, where available.



Location Map

Hydrogeology Study
Troublesome Aquifer

Greater Pole Creek Basin

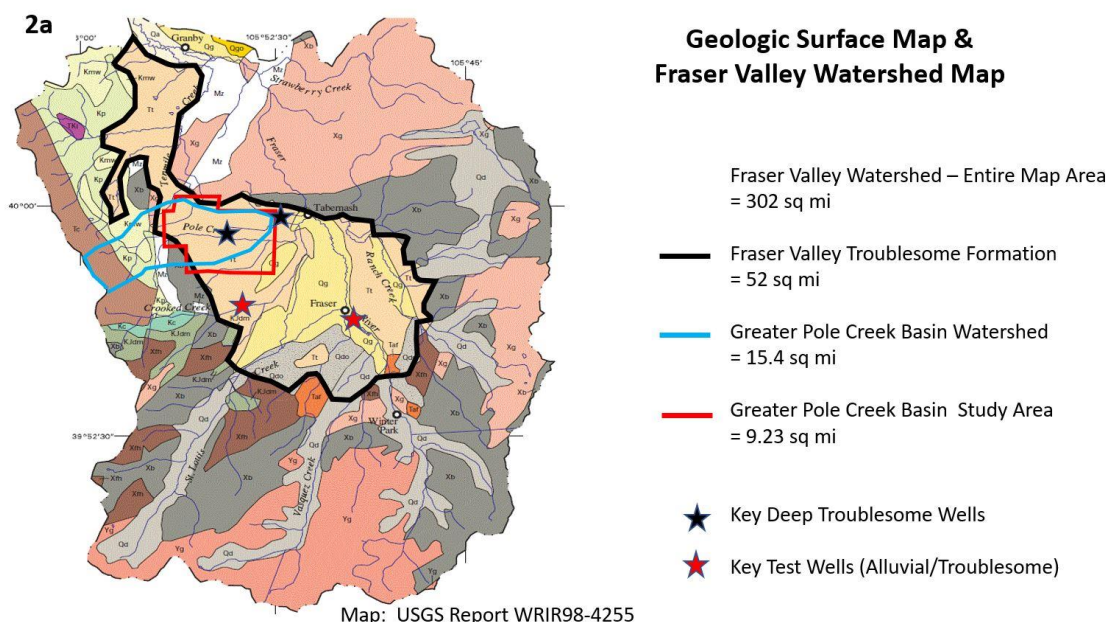
NW Fraser Valley,
Grand County, Colorado

- Hydrogeology Study Area
- Fairways at Pole Creek Dev
- Pole Creek Meadows Dev
- Key Deep Troublesome Wells
- Key Test Wells (Alluvial/Troublesome)

Figure 1-1a, 1-1b. The Fraser River Watershed in north-central Colorado (**1a**) with Study Area (**1b**) extent depicted by the red boundary, and the Fairways at Pole Creek and Pole Creek Meadows Developments bounded by the dashed black and blue lines, respectively. Locations of key deep Troublesome wells (YMCA #1& #2, TMWS #2) are shown as black stars, and two Alluvial and Troublesome test wells (CCR #1, WPR #7) are depicted with red stars.

1.2 - Location and Geological Setting

The Greater Pole Creek Basin study area lies within an intermountain basin in the northwest portion of Fraser Valley, Grand County, Colorado, and includes six residential developments; the largest are The Fairways at Pole Creek and Pole Creek Meadows (**Fig 1-1b**). The study extends over portions of the drainage areas of Pole Creek and Skunk Creek to the south, and Thomas Creek to the north (not visible in Figure 1), all tributaries to the Fraser River. The Troublesome Formation includes most of the semi-consolidated sediment underlying the study area, consisting primarily of silt with intermixed stringers of sand (Shroba, and others, 2010). The younger and much thinner sediments in the Alluvial Aquifer, situated above the Troublesome Formation in the center of the valley (**Fig 1-2a, 1-3a, 1-3b**) are composed mostly of sand and gravel. The total thickness of the Troublesome Formation is not definitively known but is estimated at approximately 1000 ft toward the center of the Fraser Valley Basin (Shroba, and others, 2010, p. 14) whereas the alluvial section thickness varies from 0 to approximately 140 feet (Bausch and Bails, 2004, p 24-28). Aquifers in both formations serve as domestic and municipal water sources in the valley, whereas the surrounding higher terrain is generally underlain by fractured crystalline basement rocks that yield smaller amounts of water, although still usually suitable for domestic needs (**Fig 1-3b**). Each of these underground water sources have unique hydraulic properties and may have different water-quality characteristics based on the age and time of exposure to various crystalline rock and/or sediment.



2b

Legend Geologic Surface Map & Fraser Valley Watershed Map

Unconsolidated surficial deposits		Sedimentary rocks of Cretaceous age	
Qa	Modern alluvium	Kmw	Windy gap member of Middle Park Formation
Qg	Gravels and alluviums	Kp	Pierre Shale, undivided
Qgo	Older gravels and alluviums	Kc	Colorado Group
Qd	Glacial drift of Pinedale and Bull Lake Glaciations	Sedimentary rocks of Cretaceous and Jurassic age	
Qdo	Older glacial drift (pre-Bull Lake age)	KJdm	Dakota and Morrison Formations
Igneous rocks of Tertiary and/or Cretaceous age		Sedimentary rocks broadly classified	
TKi	Laramide intrusive rocks	Mz	Mesozoic rocks – Mainly early Cretaceous, Jurassic, and Triassic age
Taf	Ash flow tuff of main volcanic sequence	Igneous and metamorphic Precambrian-age rocks	
Sedimentary rocks of Tertiary age		Yg	Granitic rock of 1,400 Ma
Tt	Troublesome Formation – Siltstone, sandstone, and conglomerate	Xg	Granitic rock of 1,700 Ma
Tc	Coalmont Formation – Sandstone, shale, coal beds, and conglomerate	Xb	Biotite gneiss, schist, and migmatite
		Xfh	Felsic & hornblende gneisses, either separate or interlayered

Map: USGS Report WRIR98-4255

Figure 1-2a, 1-2b. Surface geologic map (2a) and geological legend and explanation (2b) of the Fraser River Basin and surrounding watershed (from Apodaca and Bails, 1999).

Fraser Valley - Alluvial, Troublesome & Fractured Aquifers Generalized Geologic Map and Cross-Section

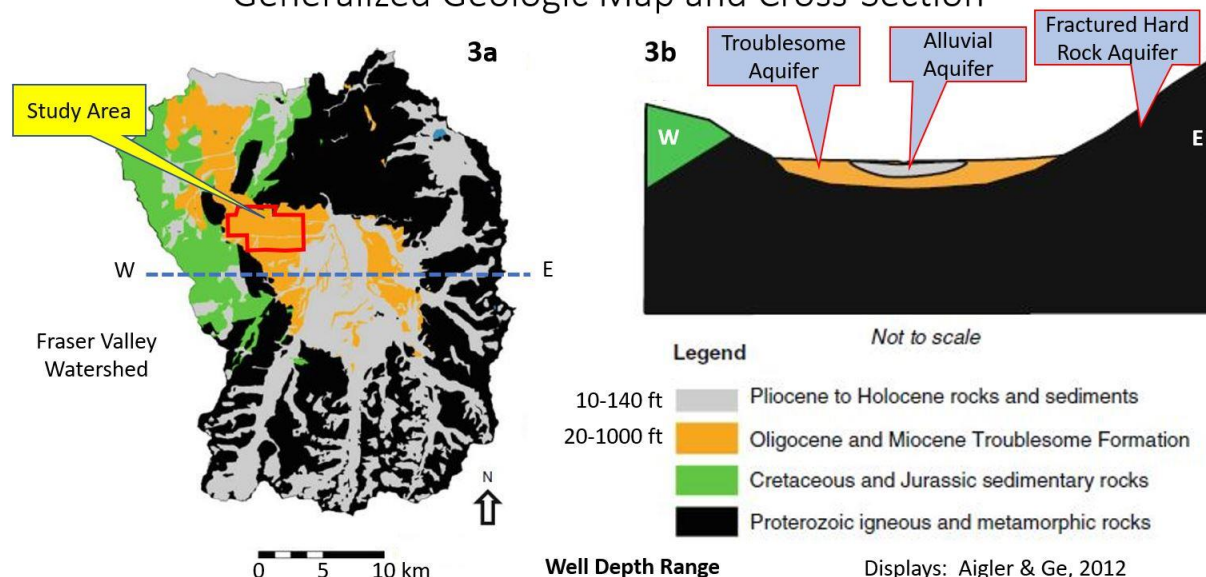
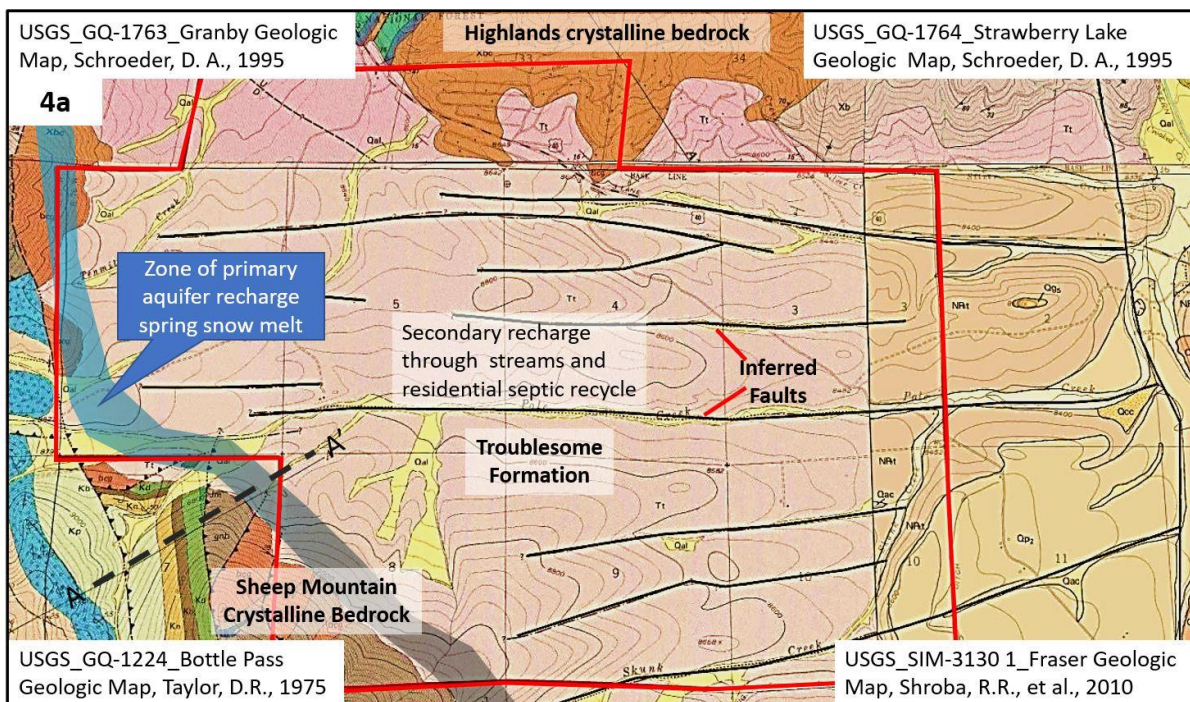
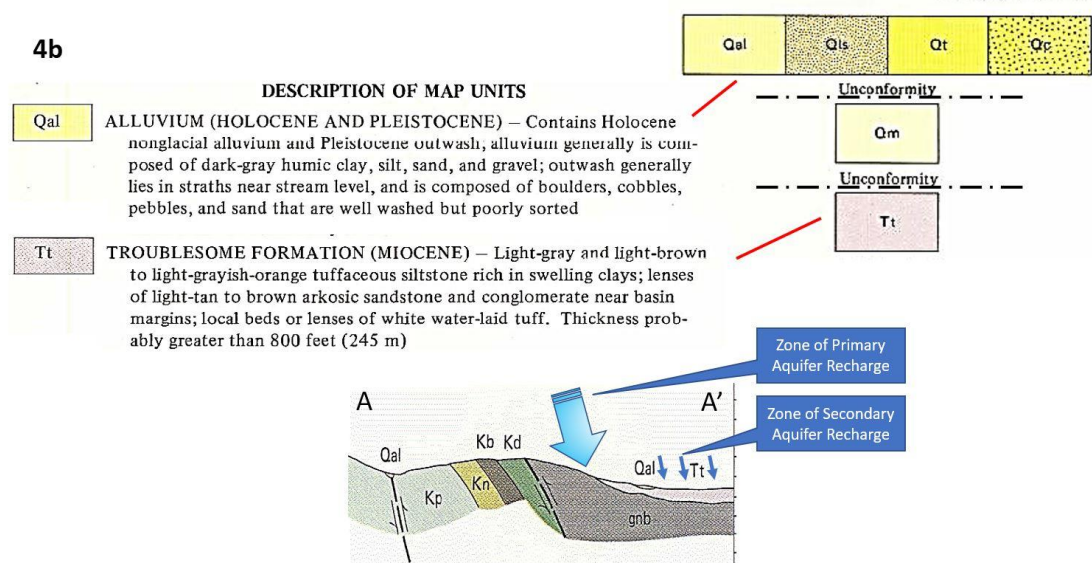


Figure 1-3a, 1-3b. Generalized geologic map (3a) and east-west transect (3b) across the Fraser River Basin. The cross section depicts the relative position in the basin and thickness of the Alluvial, Troublesome, and fractured-rock aquifers (from Aigler and Ge, 2012).

The Alluvial and Troublesome aquifers are recharged primarily by spring snowmelt (Bauch, 2000, p 7). Most of the water entering the Alluvial and Troublesome Aquifers originates along the margins of the basin adjacent to the higher-elevation mountain bedrock. Additional “secondary” aquifer recharge is supplied by basin-wide infiltration of precipitation, streams, and recharge from domestic septic system leach fields (**Fig 1-4a, 1-4b**). With no widespread overlying impermeable layer, the Troublesome Aquifer is considered “unconfined” and in direct connection with the surface and atmospheric pressure. A hypothetical cross section (**Fig 1-5**) demonstrates the aquifer structure in the basin, including primary sources of aquifer recharge (Colorado Groundwater Atlas, ONO-010, 2020). Additional detail is included in **Section 2.1** associated with the water-table / potentiometric map. Volumes of aquifer recharge are discussed in **Section 3.2** and water-quality variations associated with recharge flow dynamics are discussed in **Section 5.2**.





USGS_GQ-1224_Bottle Pass Geologic Map, Taylor, D.R., 1975

Figure 1-4a, 1-4b. Surface geologic map(s) (4a) view of the study area with cross section along transect A-A' showing primary groundwater recharge zone for the Troublesome Aquifer (USGS Bottle Pass Geologic Map, Taylor, 1975, USGS Granby Geologic Map, Schroeder, 1995, USGS Strawberry Lake Geologic Map, Schroeder, 1995, USGS Fraser Geologic Map, Shroba, and others, 2010). Description of map units for the Alluvial and Troublesome Formations along with geologic profile of transect A-A' are shown on 4b.

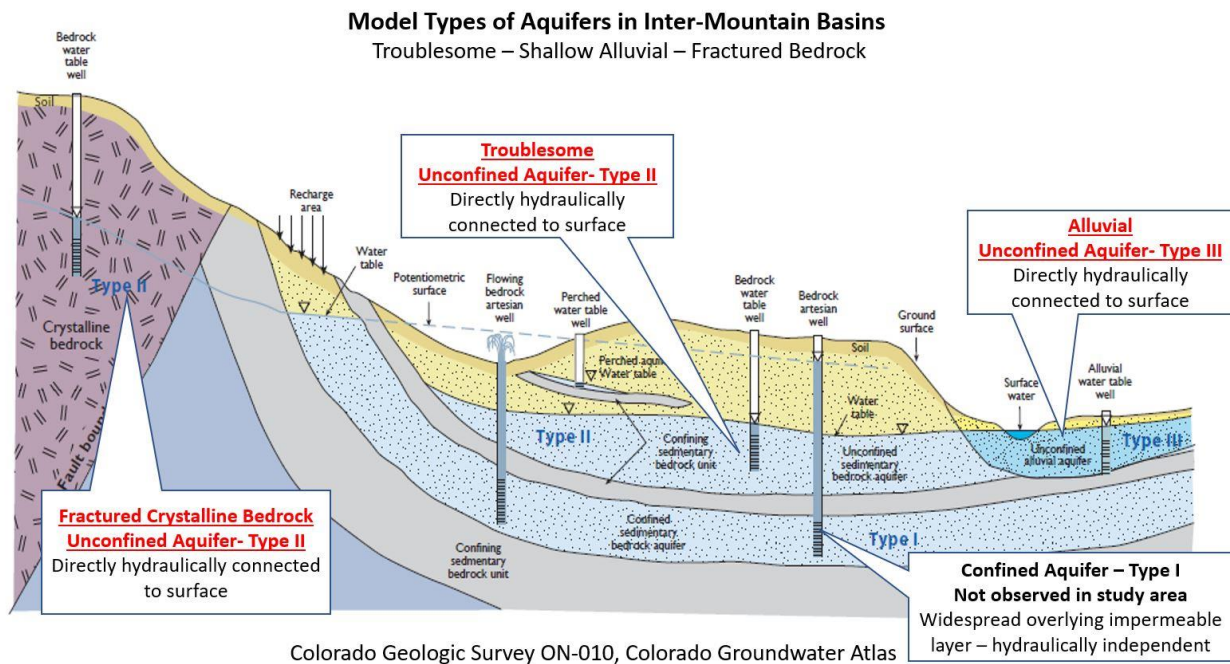


Figure 1-5. Generalized cross section of types of aquifers observed in inter-mountain basins in Colorado. The unconfined Alluvial and Troublesome Aquifers are present in the study area.

The Troublesome Formation aquifer system is composed of upper and lower aquifer intervals, although there is no definitive wide-spread boundary between the intervals. Based on drilling logs from deeper wells that penetrate the Lower Troublesome, sand percentage is larger in this lower section. Where not covered by shallow alluvial sediments, the upper portion of the Troublesome formation is exposed at the surface and varies in thickness from 0 to approximately 400 feet. Almost all domestic wells in the study area are completed in the upper portion of the Troublesome Aquifer. A few deeper wells penetrate the lower section of the Troublesome, where aquifer hydraulic properties and water quality are substantially more variable. This report documents these differences to the extent possible, given the limited number of well records. Although the Troublesome Aquifer within the Greater Pole Creek Basin is the main source of groundwater, this study also describes the hydraulic properties and water quality of the overlying, smaller areal extent of the Alluvial Aquifer for comparison purposes.

1.3 - Available Well-Log Data

Prior to most residential development, the first documented report of the Troublesome Aquifer in the study area was conducted in 1997 and amended in 1998 by Bishop-Brogden Associates (BBA, 1998). That report included logs from 33 wells. As of 2022, hundreds of additional wells have been completed in the Upper Troublesome Aquifer. This report evaluates 269 wells, with 145 wells having drilling logs deemed of sufficient quality for aquifer evaluation (**Fig 1-6**). Statistical summaries of well data are provided on **Tables 1-1a and 1-1b**. (All extracted and interpreted well data used for these analyses are tabulated and available via USGS Science Data Catalog (Rosenberry and Stoughton (2024)).

Details contained in drilling logs range considerably and subjective assessments were made regarding the usability of the data. Drilling logs were determined to be of poor, fair or good quality. Only those drilling logs that documented detailed drilling and sediment depths, sediment type and water sand depths were deemed good quality. Examples of poor and good quality logs are depicted on the cross section (e.g., **Fig 1-7**). Only one well, municipal well TMWS#2, in the study area included geophysical logs (**Fig 1-8, 5-5**) with the associated drilling logs (**Appendix-Table A3-2a, A3-2b**), both determined to be of excellent quality. Information from 145 good-quality drill logs was assembled to create aquifer-wide interpretations of geological properties and vertical extent profile (**Fig 1-9**). Well locations recorded in state records often were not sufficiently accurate and many wells (approximately 20 percent) required re-positioning aided by Landsat imagery before determining proper elevations necessary for accurate water-table mapping (**Section 2.1**).

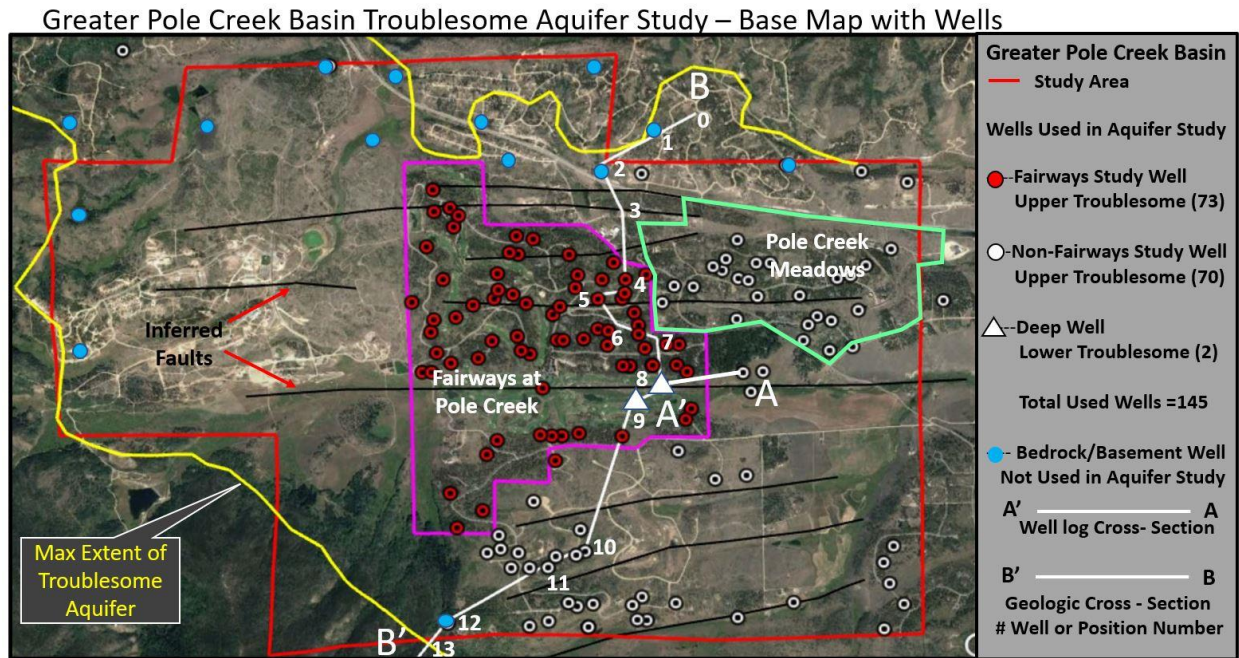


Figure 1-6. Mapped locations of wells whose logs were used to determine the Troublesome Aquifer hydrogeological properties. Numbered wells or locations correspond to locations depicted in **Figure 1-9**.

Table 1-1a. Statistical summary of well data taken from 145 selected drilling logs used water table measurements and upper most saturated sand elevations. Data values shown with yellow background include: measurements of surface elevation (Surf Elev), well depth (Well Depth), total well depth elevation (TD Elev), water table depth measured by water static depth at time of pump installation (Pump West/Z), water table static depths relative to the average hydraulic gradient (Wst Dist Hyd Grad) (**Fig 2-2**), depth to top of uppermost sand within saturated section (T sand Z), top of uppermost sand elevation within saturated section (T Sd Elev) and interval thickness of top of uppermost saturated sand to well total well depth (Tsd-TD).

Table 1-1b-part 1. Statistical summary of well data taken from 145 selected drilling logs used for deriving Upper Troublesome aquifer specific yields, based on total depth drilled. Data values shown with green background include number of sands drilled below water table (Number Sands), thickness of saturated section from water table to bottom of well (Well Sat Int/TD), total thickness of all sands combined (Total Sand Thick), the ratio of total sand thickness to total saturated thickness (Sat int Net/Gross).

Table 1-1b-part 2. Statistical summary of well data taken from 145 selected drilling logs used for deriving Upper Troublesome aquifer specific yields, based corrections to a normalized 400 ft drilling depth. Data values shown with blue background are adjusted to the reference 400 ft drilling depth, total well depth corrections (Adjustment TD-Ref Z), thickness of saturated interval assuming a common 400 ft well depth (Ref Z Adj Sat Int), adjusted total sand thickness assuming a 400 ft well depth (Ref Z Adj Sd Thick), adjusted non-sand thickness assuming a 400 ft well depth (Ref Z Adj Non Sd Thick).

Average P(50) case, 10 percent probability value P(10) and 90 percent probability value P(90) cases are shown for each parameter and were used to derive water storage volumes and weighted average specific yields (Sy) for the Upper Troublesome Aquifer in the Greater Pole Creek Basin.

Statistical values (normal distribution) of data taken from selected 145 wells with good quality drilling records
Data based on total depth drilled for each well ranging from 130-800 feet

1a		# Wells	Statistic	Surf Elev	Well Depth	TD Elev	Pump Wst/Z	Wst Dist Hyd Grad	T sand Z	T Sd Elev	Tsd-TD
Development Area			St Dev				48	46	58	109	110
Fairways at Pole Creek	75	Min	8440	130	7994	0	-142	53	8308	25	
Pole Creek Meadows	28	Low-P(10)				34	-61	99	8345	41	
Pole Creek Timbers	42	Av-P(50)	8657	356	8301	96	-2	173	8484	183	
Sheep Mountain Estates		High-P(90)				158	58	247	8624	324	
Other Nearby		Max	9067	800	8667	266	146	372	8857	640	

1b		# Wells	Statistic	Number Sands	Well Sat Int/TD	Total Sand Thick	Sat Int Net/Gross	Adjustment TD-Ref Z	Ref Z Adj Sat Int	Ref Z Adj Sd Thick	Ref Z Adj Non Sd Thick
Development Area			St Dev	1	117	5	0	126	48	14	46
Fairways at Pole Creek	75	Min	1	60	2	0	-400	134	2	131	
Pole Creek Meadows	28	Low-P(10)	1.4	110	4.1	0.6%	-118	242	1.0	226	
Pole Creek Timbers	42	Av-P(50)	2.3	260	10.9	6.0%	44	304	18.5	285	
Sheep Mountain Estates		High-P(90)	3.3	410	17.7	11.3%	206	366	36.0	345	
Other Nearby		Max	5	648	29	0	270	400	70	383	

Total = 145

Total Depth Drilled
Average sand thickness=
Ave total sand thickness/Ave number of sands =
10.9/2.3 = 4.7 feet

Reference 400 ft Depth Drilled
Statistical values used for Sy calculations
after each well's data extrapolated to a
reference/common 400 ft drilling depth

Key Type Logs/Correlations – Drilling Reports

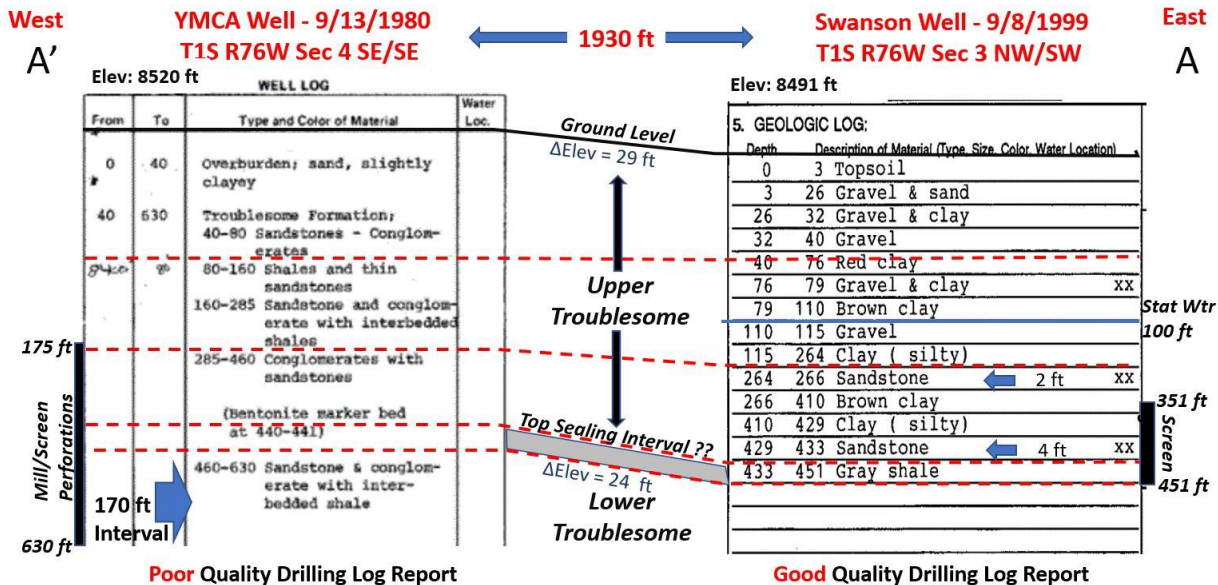


Figure 1-7. Well cross-section A'-A, depicted in Figure 1-6, illustrates examples of drilling logs determined to be of poor quality (left) and good quality (right), including authors' interpretive notes. Logs also demonstrate the sediment correlation between wells and possible separation of the upper and lower portions of the Troublesome Aquifer. Logs depths are not linearly displayed with interpreted red dashed lines correlating similar intervals and

approximate marker beds in each well. Black bars adjacent to the drilling logs represent depth of well screens. The deep YMCA well (left) penetrated a total of 170 feet of the interpreted Lower Troublesome Aquifer.

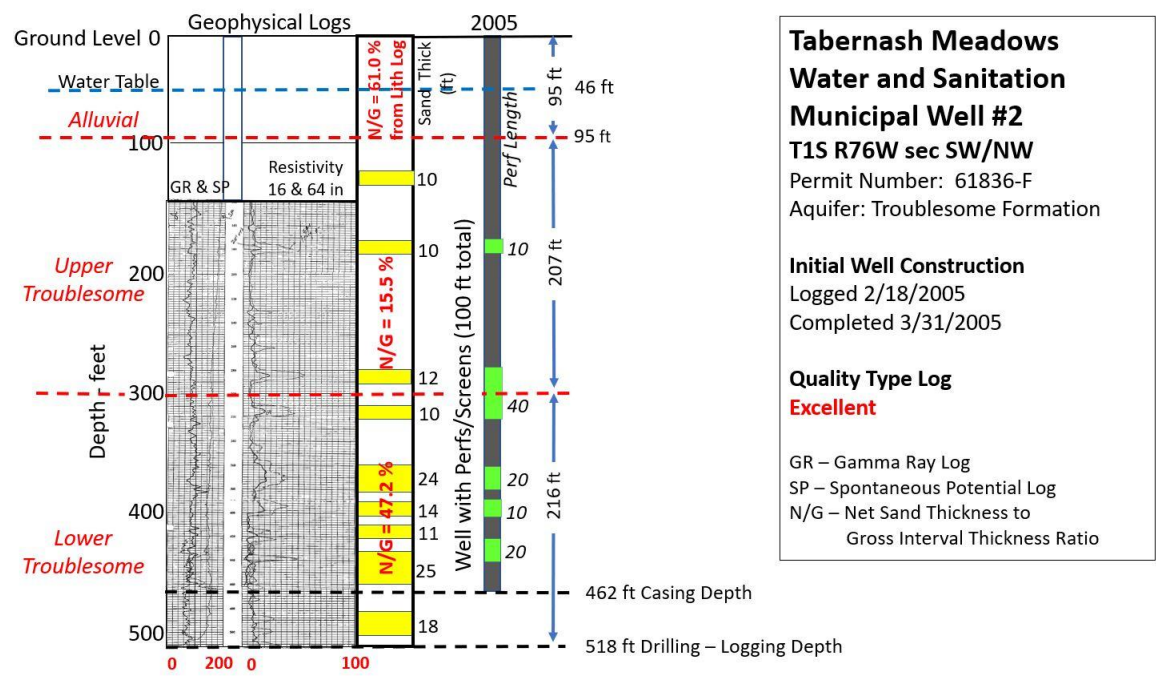


Figure 1-8. Drilling and geophysical logs from TMWS #2 well and were determined to be of excellent quality, including authors' interpretive notes. Sand intervals based on resistivity log interpretation (**Fig 5-5**) and drilling lithology log description (**Appendix-Table A3-2a, A3-2b**).

Greater Pole Creek Basin Geologic Cross-Section

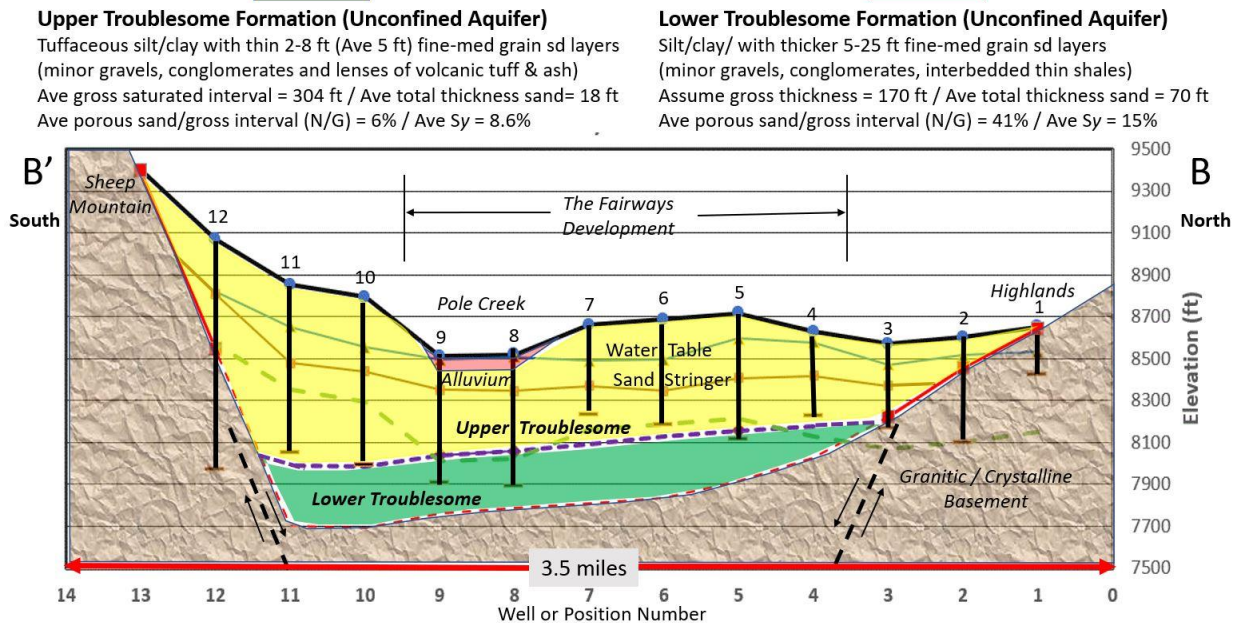


Figure 1-9. Geologic schematic cross section B'-B as depicted on map (**Figure 1-6**) with referenced well/position number (horizontal distances between wells are not to scale). Interpreted aquifer layering and vertical extent based on summarizing drilling logs. General description of sediment content of Upper and Lower Troublesome, average net sand / gross interval and average specific yield included. Exposed surface rock and sediment along with wells near the margins of the basin help define the tilted fault bounded basement structure.

Four key wells are referenced within this report, and their mapped locations are depicted with black and red stars in **Fig 1-1b, 1-2a**. These include two deep wells extending into the Lower Troublesome interval. The older of the two, drilled in 1980 and referred to as the “YMCA well,” is in the central portion of the study area and was drilled to a total depth of 630 feet for irrigation and augmentation purposes. Log cross-section A'-A (**Fig 1-7**) depicts this associated poor-quality drilling log (left) correlated with a good quality drilling log from a nearby domestic well drilled in 1999 (right). The mapped position of the cross-section A'A is shown on **Fig 1-6** (white line). This good-quality log is representative of other good-quality logs used for this study with detailed depths of sediment layers, good descriptions of sediment type and water-level depths. The more recent 2005 Tabernash Meadows Water and Sanitation municipal well (TMWS #2) is located immediately adjacent to the north-eastern boundary of the study area, just west of Tabernash (**Fig 1-2a**, right-most black star). This deep well (518 ft) was drilled to supplement municipal water supplied by the two shallow wells (TMWS #1 & #3) that tap the Alluvial Aquifer. Fortunately, this deep Troublesome well includes both a drilling log and geophysical logs (the only known geophysical well logs in the basin), thus allowing the best definition of thickness and depth of individual sand intervals. The representative excellent-quality logs (**Fig 1-8, 5-5**) include gamma ray (GR), spontaneous potential (SP) and two resistivity logs (16" short normal and 64" long

normal). The two resistivity logs are mostly diagnostic for sand definition, whereas the gamma-ray log can demonstrate the presence or absence of possible low-permeability shale intervals.

Two other key test wells south of the study area (**Fig 1-1b, 1-2a**, red stars) were used for assessing detailed hydraulic properties for both the Troublesome and Alluvial Aquifers (Aigler & Ge, 2012). This report also integrates data from other previous studies and well tests to estimate the hydraulic properties of these aquifers (**Section 3.3**).

The approximate relative thickness of the upper and lower portions of the Troublesome Aquifer in context of the basin structure is depicted by cross-section B'-B (**Fig 1-9**). The mapped position of the cross-section is shown on **Fig 1-6** (white line) along with reference well/position numbers. The cross section that traverses north to south through the Pole Creek Basin and across the Fairways Development also shows relative elevations of the underlying and adjacent crystalline basement rock (**Fig 1-9**). Exposed crystalline rock at land surface and wells near the margins of the basin help define the tilted fault bounded crystalline basement structure.

The cross-section B-B' extends through several wells across the study area. Only two, both designated irrigation/augmentation wells (#8 & #9) and adjacent to Pole Creek, extend to the Lower Troublesome whereas all other domestic water wells stop short of this lower interval. Total thickness and sediment make-up of the lower interval is uncertain, given fewer well logs, although it appears to have higher sand content, as indicated by the well log for TMWS #2 well (**Fig 1-8, 5-5**). A summary of the study's derived aquifer properties and average water yield percentages (discussed subsequently) are shown on **Fig 1-9**.

The exchange of water between the Troublesome Aquifer and the surrounding crystalline basement rock fracture system is quite complex and related to aquifer recharge (Heath, 1983; Markovich, et al, 2019). Assessment of this water interaction is not included in this study.

1.4 - Troublesome Formation Aquifer System - Hydrogeological Parameters and Estimated Water Volumes

1.4.1 Determination of Aquifer Sand Intervals and Associated Specific Yield

Within an unconfined saturated sediment volume, stored water occupies the pore space between the sediment grains the percent volume of which porosity (n), varies according to sediment type. A more pertinent hydraulic property related to water supply is specific yield (S_y), the percentage of stored water that will drain via gravity from unconfined saturated sediment. The remaining water will always remain within the sediment as specific retention (S_r). The summary relationship is:

The relative percentages of S_y and S_r are dependent upon type of sediment and associated grain size, shape and sorting. Generally, S_r increases with decreasing grain size. Even though small grain size silt and clay may have considerably high porosity, most of the water is retained and therefore S_y is commonly very small. Conversely, the larger grain sized sand and gravel typically have larger S_y and water-supply wells are usually screened in these sediments.

Figure 1-10 depicts the general relation between porosity, specific yield and specific retention along with sediment grain size. The key sedimentary constituents, clay/silt and fine sand within the Troublesome Aquifer are noted on the graph along with this study's assigned average specific yield and range.

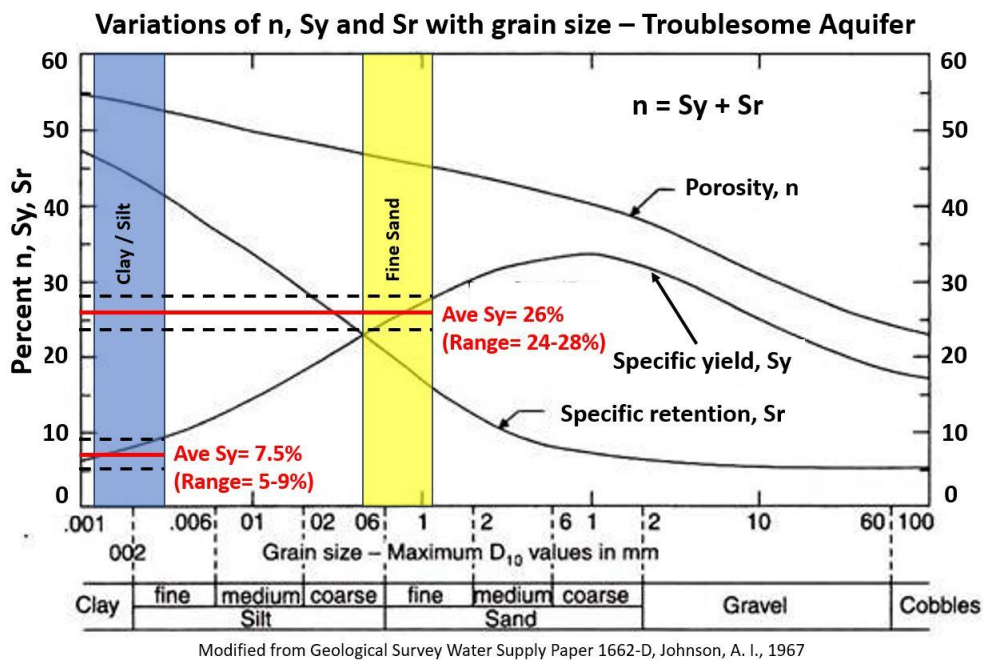


Figure 1-10. Graphed trend values and relationship for specific yield (S_y), specific retention (S_r) and porosity (n) parameters for unconsolidated sediments based on particle size (modified from Johnson, 1967, p D22). Assigned average specific yields and ranges for Troublesome Aquifer sediment are noted.

The most recent comprehensive study of Fraser Valley geology and specifically the Troublesome Formation, Shroba et al. (2010) has indicated the upper portion of the Troublesome is composed predominately of semi-consolidated clay and silt with relatively minor amounts of fine to medium sand. Based on this study's synthesis of well data, the average depth from land surface to the water table is 96 feet (**Table 1-1b**). All sediment below the water table is assumed to be saturated since the Troublesome is semi-consolidated and an unconfined aquifer. Based on evaluation of all referenced drilling logs, the wells encounter 1-5 water bearing units (average 2.3) of fine- to medium-grain silty-

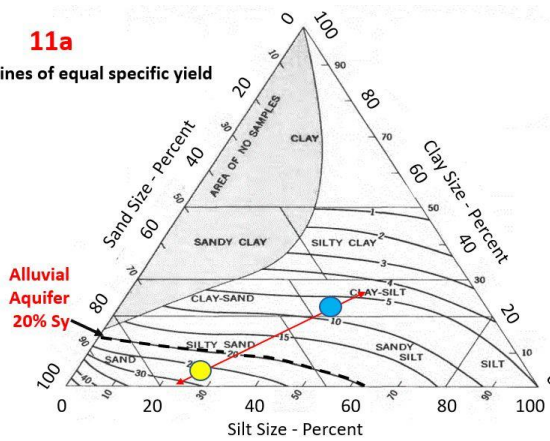
sands with individual unit thickness ranging from 2-29 feet. Adding all encountered sand units in each well, the total sand thickness average across all wells is approximately 11 feet with an average single sand thickness of 4.7 feet (**Table 1-1b**). The distribution of Troublesome sediment types in the study area appears to be a composite of interfingering layers of sand separated by massive silt and clay intervals. Sand layers are the targeted intervals for most of the water-well production. The percentage of sand thickness (net) relative to the total saturated section (gross) is generally referred to as net/gross (N/G). Based on data from 145 wells, for the Upper Troublesome, the average N/G is approximately 6 percent. The N/G estimate observed in the “key” Troublesome TMWS #2 well (**Fig 1-8**) is based on higher-precision geophysical logs (**Fig 5-5**) and detailed drilling lithologic logs (**Appendix-Table A3-2a, A3-2b**). In this drill hole, the Upper Troublesome lies beneath 95 feet of Alluvial-Aquifer sediment and includes 32 feet of sand in a gross 207-foot saturated section, resulting in a N/G of 15.5 percent.

Incorporating information from published studies, lab measurements, pumping tests and aquifer analogs (Johnson, 1967, Geologic Water Supply Paper 1662-D, **Fig 1- 11a, 11b, 11c**), sand intervals have been assigned a S_y of 26 percent and silt/clay intervals are assigned a value of 7.5 percent. Annotations in **Fig 1-11a** for assigned S_y of sand (yellow) and silt (blue) are posted on the Textual Classification Triangle as well as the S_y vs Particle Size / Lithology Cross Plot (**Fig 1-11b**). Average S_y for given lithologies/grain size based on numerous analog aquifers (**Fig 1-11c**) aided in the S_y assignment for the Upper Troublesome sediment. Assuming 304 feet of saturated sediment within a gross interval of 400 feet with an average of 18.5 feet of sand and 285.5 feet of silt (**Table 1-1b**), the overall weighted average S_y (silt and sand) of the entire Upper Troublesome Aquifer is 8.6 percent (range: 5.1% - 10.9%). This S_y value and associated range were used for accessible storage water volume calculations.

When assessing the Fraser Valley underground aquifer volumes, a USGS report (Apodaca, and others, 1999) assigned S_y a value of 20 percent for alluvial sediments and 12 percent S_y for the Troublesome. The BBA Hydrology Report (BBA, 1998) and USGS publication (Bauch, and others, 2004) implemented a constant specific yield of 20 percent for both Troublesome and Alluvial aquifers volume calculations. For comparative purposes, the 20 percent S_y annotation is shown in **Fig 1-11a** and **1-11b**.

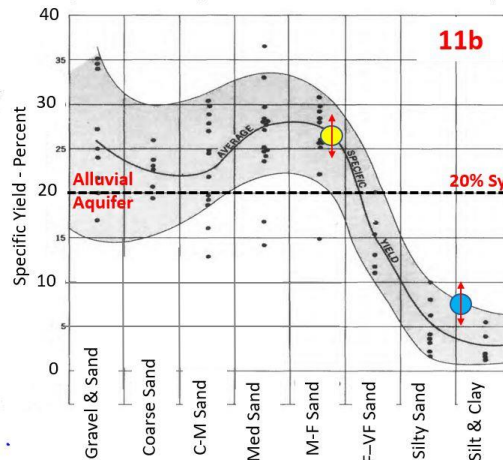
Textural Classification Triangle for Unconsolidated Materials
(Showing Relationship between Particle Size and Specific Yield)

11a
Lines of equal specific yield



Geological Survey Water Supply Paper 1662-D, Johnson, A. I., 1967

Statistical Relation of Specific Yield to Particle Size
(Sediments Sampled at Kechna Doab, West Pakistan)



Range of Lithologies Described from Well Drilling Logs – Greater Pole Creek Basin - Upper Troublesome Aquifer

● Clay – Fine Silt: Ave Sy=7.5% (Range=5%-9%) ● Fine – Med Silty Sand: Ave Sy=26% (Range=24%-28%)

Compilation of Specific Yields for Various Materials – Based on Producing Aquifer Analogs
(All values rounded to the nearest percentage)

Material	Valley fill, California (Eckis, 1994)	Mokelumne area, California (Piper and others, 1939)	Santa Ynez River basin, California (Upson and Thomasson, 1931)	Sacramento Valley, Calif. (Poland and others, 1946)	Smith River plain, California (Back, 1967)	Ventura County, Calif. (Calif. Water Resources Board, 1956)	Santa Margarita Valley, Calif. (Calif. Dept. Public Works, 1956)	Tia Juana Basin, Calif. (Calif. Water Rights Board, 1957)	San Luis Obispo County, Calif. (Calif. Water Resources Board, 1958)	San Joaquin Valley, Calif. (Davis and others, 1959)	Eureka area, California (Evenson, 1959)	Santa Ynez Basin, Calif. (Wilson, 1959)	Kechna Doab, Pakistan (Kazmi, 1961)	Napa-Sonoma Valleys, Calif. (Kunkel and Upson, 1960)	Humboldt River Valley, Nev. (Cohen, 1963)	Unconsolidated alluvium (Preuss and Todd, 1963)	Little Bighorn River valley, Montana (Moulder and Others, 1966)	Average specific yield
Clay.....	1	4	2	3	1	0	10	1	3	3	3	5	3	3	1	4	17	2
Silt.....	10	4	12	3	3	3	10	10	5	5	10	5	5	5	19	4	17	8
Sandy clay.....	10	4	12	3	3	5	5	5	5	5	10	10	10	10	20	23	32	7
Fine sand.....	21	26	12	10	10	25	25	25	25	25	20	20	27	20	26	23	32	21
Medium sand.....	31	26	30	20	15	25	28	30	25	25	20	30	28	20	28	28	32	26
Coarse sand.....	31	35	35	20	25	25	28	32	25	25	20	30	23	20	27	28	32	27
Gravelly sand.....	31	35	35	20	25	21	22	28	21	25	20	20	23	20	27	22	32	25
Fine gravel.....	27	35	35	25	25	21	22	26	21	25	25	25	26	25	19	17	25	25
Medium gravel.....	21			25	25	21	22	23	21	25	25	25	26	25	13	13	25	23
Coarse gravel.....	14			25	25	21	22	18	21	25	25	25	26	25		12		22

Geological Survey Water Supply Paper 1662-D, Johnson, A. I., 1967

Range of Lithologies Described from Well Drilling Logs – Greater Pole Creek Basin - Upper Troublesome Aquifer

● Clay – Fine Silt: Ave Sy=7.5% (Range=5%-9%) ● Fine – Med Silty Sand: Ave Sy=26% (Range=24%-28%)

Figure 1-11a, 1-11b, 1-11c. Values for specific yield (S_y) for unconsolidated sediments based on particle size and shape (11a, Johnson, 1967, p D8), laboratory measurements from well samples (11b, Johnson, 1967, p D63), and summary of studies of analog aquifers based on pumping tests, laboratory measurements and theoretical estimates (11c, Johnson, 1967, p D70). For this study, S_y estimates for silt/clay (blue dot annotation) and medium grain size sand (yellow dot annotation) are depicted on 11a and 11b as well as annotation for a constant S_y of 20%. S_y values from Aquifer analogs are shown on 11c. This study's assigned average S_y and range are displayed below the figure.

The Lower Troublesome interval has been characterized based on two closely spaced wells in the central portion of the study area, one referenced previously as a “key” well (YMCA, **Fig 1-7**, left). The poor-quality drilling log indicates this well is composed of more massive sand units with average thickness of approximately 70 feet, which constitutes a N/G of 41 percent of the 170-foot drilled interval. The weighted average S_y is estimated at approximately 15 percent and with values for specific intervals ranging from 13% - 17%. The logs from the other deep “key” Troublesome well (TMWS #2) drilled immediately along the northeastern boundary of the study area indicates a similar and well-constrained 104 feet of sand interval resulting in a N/G of 47% within the vertical interval of 216 feet. The total aquifer thickness is uncertain.

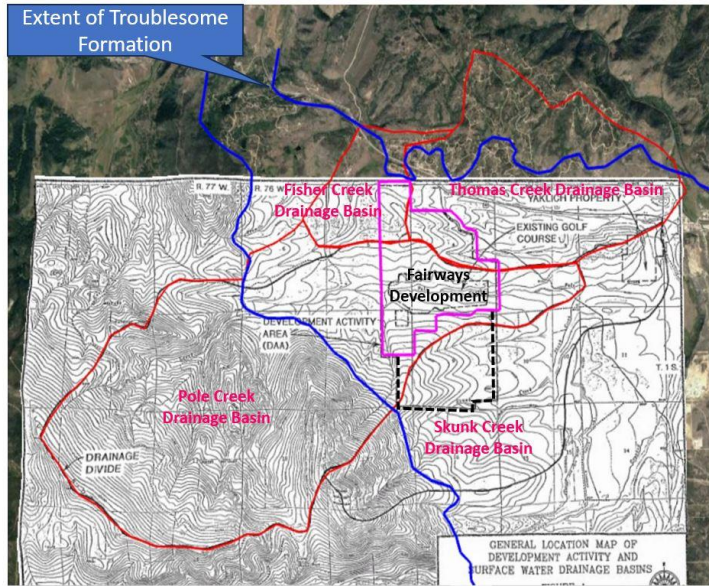
A two-well cross-section A'-A is shown mapped on **Figure 1-6**. Data from the two wells that bound section A'-A (**Fig 1-7**) indicates a possible impermeable or low-permeability shale interval that separates the Upper and Lower sections of the Troublesome aquifer. The YMCA well drilling log, shown on the left side of the cross-section, extends into the Lower Troublesome and documents a bentonite marker usually found in impermeable clay/silt or “shale” units. In addition, the nearby Swanson well drilling log, shown on the right side of the cross-section (**Fig 1-7**), indicates a “shale” unit at the bottom of the well borehole and correlates with the YMCA inferred “shale” unit. Although data from these two wells indicate that portions of the Lower Troublesome aquifer may be confined, other data do not. The gamma ray log from the subsequently drilled deep TMWS #2 well demonstrates no apparent shale unit separating the two intervals (**Figs 1-8, 5-5**). The latest unofficial memos and communications from the Colorado State Engineering Office (SEO) indicate there is no separation (**Appendix-Fig A3-2a, A3-2b**). The impermeable shale section separating the lower from the upper Troublesome intervals indicated in the YMCA and Swanson logs appears not to be widespread according to the updated SEO position. Therefore, in this study, we interpret the two aquifer intervals to be hydraulically connected and the Lower Troublesome is considered an unconfined aquifer.

1.4.2 Method for Determining Aquifer Extractable Water Volume

The volume of water that could be extracted from the unconfined upper portion of the Troublesome Aquifer is derived by calculating the total estimated gross sediment volume of the saturated sediments (area times thickness) multiplied by the average estimated specific yield (S_y) of the saturated interval. For the poorly documented Lower Troublesome Aquifer, a constant thickness (170 ft) and specific yield was used. Total basin extractable water volume is the sum of the two aquifer estimates.

The aquifer area was determined based on several reports. The Greater Pole Creek Basin, including the Fairways Development, covers portions of three drainage sub-basins (Pole Creek, Thomas Creek, Fisher Creek) whereas the BBA 1998 Report covers two drainage basins (Pole Creek, Skunk Creek), including the developed area south of Fairways (**Fig 1-12**). Using the total Troublesome aquifer areas within these

drainage basins, the current study (4,888 acres) is slightly larger than indicated in the BBA 1998 report (4,780 acres) but is essentially equal (**Table 1-2**). This study used the surface area noted above for the Upper Troublesome and assumed the Lower Troublesome areal extent is 80 percent (3910 acres) of the Upper Troublesome due to the assumed bowl-like basin geometry at depth.



Greater Pole Creek Basin – Drainage Sub-Basins

Current Study versus 1998 BBA Report Map

Comparison:

- Fairways Development covers portions of three watershed drainage sub-basins: (Pole Creek, Thomas Creek, Fisher Creek)
- BBA 1998 Report covers two watershed drainage sub-basins: (Pole Creek, Skunk Creek)
- Outline Sources:
BBA 1998 Report Map
USGS Watershed Outline
USGS Surface Geologic Maps
2022 Potentiometric Map

Figure 1-12. Map of Greater Pole Creek Watershed including aquifer sub-basins, mapped area for Troublesome Aquifer.

Table 1-2. Summary of watershed areas used for volumetric calculations and comparison with BBA report (1997).

Drainage Sub-Basins Areas			
Areas Calculated with Google Earth - May 2022			
Watershed - Drainage Including Troublesome	Area (sq mi)	Area (acres)	Perimeter (miles)
Pole Creek	10.30	6593	15.7
Fisher Creek	1.20	765	5.39
Thomas Creek	4.81	3077	9.35
Total	16.31	10435	
Troublesome Aquifer Only			
Pole Creek	3.51	2247	9.9
Fisher Creek	1.00	640	4.2
Thomas Creek	3.13	2001	9.0
Total	7.64	4888	

Areas - BBA 1997 Hydrology Report			
Watershed - Drainage Including Troublesome	Area (sq mi)	Area (acres)	Perimeter (miles)
Pole Creek plus	15.4	9856	
Troublesome Aquifer Only			
Pole Creek plus	7.5	4780	

As mentioned above, in-place extractable water volumetric estimates are based on the thickness of the saturated interval within the aquifer. The saturated interval is the difference between the total well depth and depth to the static water table level as measured at the well. The average depth of domestic wells in this study is 356 feet, and the average depth of the water table is 96 feet (**Table 1-1b**). (Ranges of water table depths vary considerably and are shown on the statistical summary chart on **Table 1-1b**.)

There is no definitive thickness of the Upper Troublesome Aquifer. For deriving the average saturated thickness of the aquifer, having a common well depth will help reduce the uncertainty. Therefore, this study incorporated a statistical approach (normal distribution) to include a derived saturated thickness estimate for each well. The estimates include normalizing with the assumption that all wells are drilled to a common reference depth of 400 feet. Extrapolation of total sand thickness, via N/G, observed in each well was also included with the reference depths for the 400 ft case (**Table 1-1b**). A constant of 170 feet of saturated Lower Troublesome Aquifer was used for this interval and is the same thickness as one of the two wells that extended to the deeper aquifer. Uncertainty is very high for the Lower Troublesome; therefore, thickness could vary greatly.

1.4.3 Estimated Available Water Stored in the Troublesome Aquifer

Detailed statistical evaluation provides low-, average-, and high-volume probabilistic (normal distribution) cases for the reference drilling depth of 400 feet within the Upper Troublesome and are

based on variations of the aquifer as observed in well log data (**Appendix-Table A1-1a**). The average volume case would occur 50 percent of the time, whereas the low- and high-volume cases each represent a 10 percent chance of occurrence. These analyses provide a level of uncertainty in the estimate of accessible (readily pumped by wells) in-place water volumes. If only the Upper Troublesome Aquifer is considered, and assuming a 400 ft drilling depth, the average volume of extractable water equals 128,000 acre-ft (**Appendix-Table A1-1a, Fig 1-13**). This volume has been considered for integration into additional water balance analyses in **Section 3.6** since it is the primary accessible aquifer for domestic wells. The low and high estimates of accessible water volumes for the 400 ft drilling reference depth are 61,000 and 199,000 acre-ft, respectively. The average overall specific yield of 8.6 percent is derived by the proportion of accessible water versus the total saturated volume of sediment.

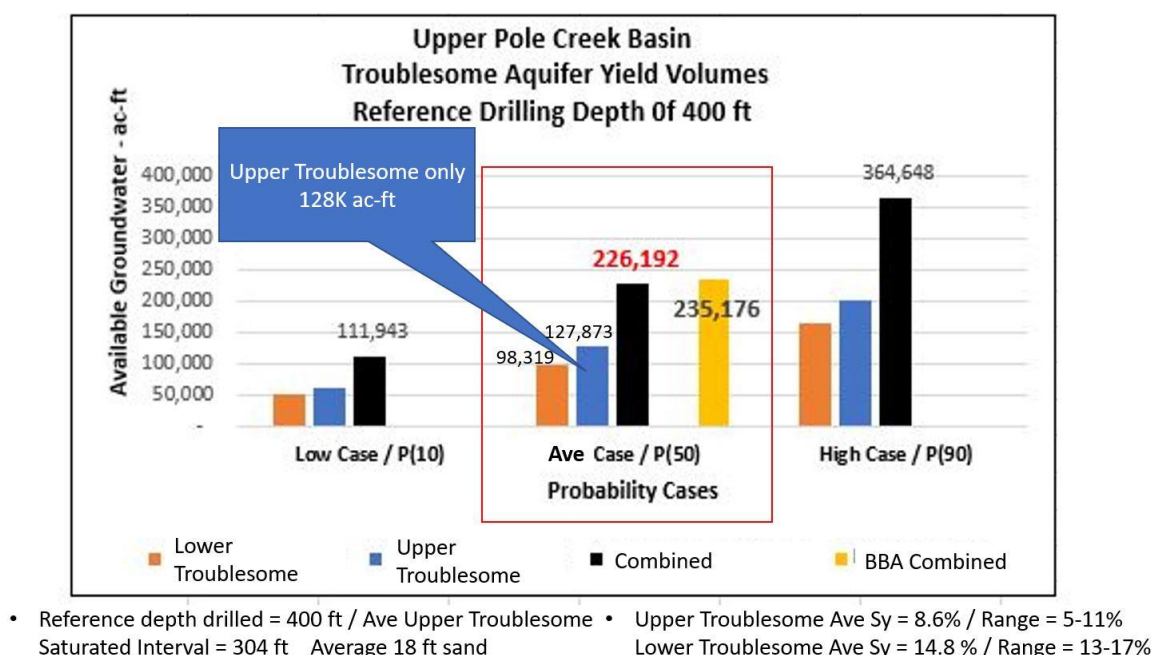


Figure 1-13. Statistical estimates of available water stored in Troublesome Aquifer are depicted with low, average, and high-volume probability cases. Each case assumes a 400 ft reference drilling depth for the Upper Troublesome and a 170 ft drilling thickness for the Lower Troublesome. Combined volumes are shown for each case along with comparisons to the BBA Water Consultants 1997-1998 estimated volumes within the average case summary. The average and range of Sy for the Upper and Lower Troublesome Aquifers are also noted.

The Lower Troublesome statistical volumes have also been derived with the assumption of 170 feet of the Lower Troublesome would have been drilled (same thickness as the YMCA well on **Fig 1-7**). The possible range of sand versus non-sand thicknesses and associated volumes resulted in an average of 98,000 acre-ft with a low side of 51,000 acre-ft and a high side range of 165,000 acre-ft (**Appendix-**

Table A1-1b). When combining both the Upper and Lower Troublesome Aquifers, the average extractable water volumes are similar to those previously published in 1997 & 1998 by BBA. This 2022 study documents an average estimate of 226,000 acre-ft (assuming 400 ft reference drilling depth) vs the BBA reported value of 235,000 acre-ft (**Fig 1-13**). The low and high estimates are approximately 112,000 acre-ft and 365,000 acre-ft respectively. (The BBA report does not provide a range of extractable volumes.)

Detailed comparison of all the volume related parameters between this current 2022 study and the BBA 1997/98 Hydrology Report is provided on the **Appendix-Table A1-2**.

Previous USGS reports (Apodaca and Bails, 1999 / Bauch and Bails, 2004) provide extractable water volume estimates for the entire Fraser Valley Basin and include the surficial Alluvial Aquifer. The emphasis of these reports was on water quality, not quantity. Therefore, most aquifer specific yield parameters were not rigorously derived. Specific yield parameters referenced in the USGS reports were taken from previously published estimates for unconfined aquifers, most applicable to sandy alluvial aquifers (20%) and not silt-dominated aquifers such as the Upper Troublesome Aquifer (8.6%). Detailed analyses and related databases were not included in the publications.

For comparison purposes with the prior USGS water reports, this current study has derived Fraser Valley-wide resource water volumes for both the Alluvial and Troublesome Aquifers. This comparison includes this study's measurement of the aquifer areas, saturated thickness assumptions and specific yield estimates (**Appendix-Table A1-3a**). The in-place water estimates for both aquifers are approximately 11.6 E^6 acre-ft and extractable water volume of 1.1 E^6 acre-ft. Apodaca and Bails (1999) report similar areas and specific yield parameter range for the Alluvial and Upper Troublesome Aquifers, with an average derived in-place water volume of 13.3 E^6 acre-ft and a derived extractable water volume of 1.7 E^6 acre-ft estimates (**Appendix-Table A1-3b**). Bauch and Bails (2004) considered the Upper Troublesome as a confined aquifer with discreet intervals of viable aquifer quantity resulting in a substantially smaller combined aquifer in-place volume of 2.6 E^6 acre-ft and extractable water of 0.5 E^6 acre-ft (**Appendix-Table A1-3c**). (Some of these volumes were not directly quoted in the referenced reports but have been derived from quoted parameters.)

2 - Troublesome Aquifer Water-Table Dynamics

2.1 Potentiometric Map

A potentiometric map, otherwise known as a water table elevation map, shows the direction and relative potential for horizontal groundwater flow within an aquifer. This map is based on the measured distance from some datum, commonly the ground-surface elevation, to the water level at each groundwater well. Contour lines, commonly called equipotential lines, are drawn on the map based on the elevations at each of the groundwater wells within the mapped area. Groundwater flow direction is interpreted to be perpendicular to the equipotential lines and the relative potential for groundwater flow is determined based on the distance from one equipotential line to the next. The closely spaced the lines, the greater potential for groundwater flow. The map also allows determination of sub-basins within the aquifer.

Within the Greater Pole Creek Basin Study Area, data from 270 wells were checked or modified to correct horizontal positioning and surface elevation (**Fig 2-1**). Approximately 20 percent of wells required revised coordinates to match with Landsat imaging. Based on statistical analyses, on-site logistical reasoning, and time required for water inside each well to reach a stable level, water-level measurements recorded at time of pump installation were deemed the most accurate and reliable (226 wells). If pump-installation water-level measurements were not available, water-level measurements made during well construction were used (44 wells). (All extracted and interpreted well data, including well-top elevations and water-table depth measurements used for these analyses, are tabulated and available via USGS Science Data Catalog (Rosenberry and Stoughton, 2024).

Preliminary mapping of the water table was based on manually drawing water-table contours that used all well data as primary “hard” control points. Topographic maps of land-surface elevation served as “soft bias” control for locations away from the primary well control points (**Fig 2-1**). Depth to the water table averages 96 feet with a range 0-266 feet (**Table 1-1b, Fig 2-2**). Shallower depths to water table occur where wells are near topographic lows and near streams, whereas deeper depths to water table occur where wells are located on or near hills or ridges.

Plotting static water-level elevation versus land-surface elevation indicates that depth to the water table increases with increasing land-surface elevation (**Fig 2-2**). The average hydraulic gradient of the Upper Troublesome Aquifer has been statistically derived from these data and demonstrates an approximate 2.7 percent slope from west to east across the study area (**Fig 2-2**).

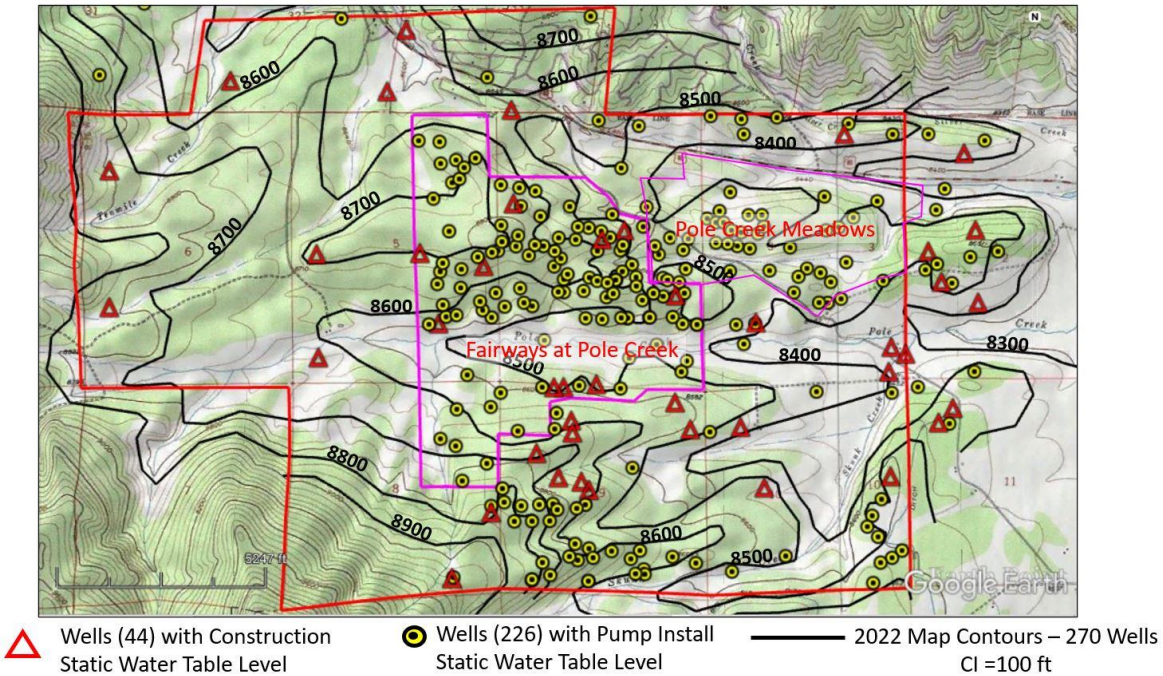


Figure 2-1. The Interim Potentiometric Map (Water Table Elevation Map) based on hand contouring of measured static water level during well pump installation (primary) and measured static water level during well construction (secondary). The water-table depth contours are overlain on the USGS topographic surface map (CI = 40 ft) and demonstrate how water-table contours often closely follow land-surface contours.

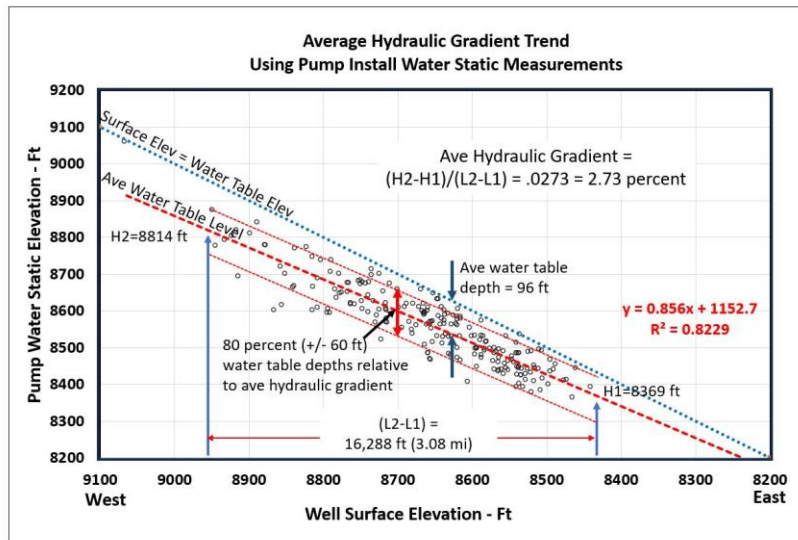


Figure 2-2. The average hydraulic gradient of the Upper Troublesome Aquifer has been statistically derived using simple linear regression from water-table measurements from 270 wells. The statistical distribution of the water table measurements demonstrates 80 percent of the values are within +/- 60 feet of the average hydraulic gradient. The gradient has been calculated as the difference between the averages in elevations between the

western and eastern portions of the study area and dividing by the distance between the western and eastern wells.

The water-table contours closely mimic land-surface contours, which is a common characteristic of an unconfined aquifer (Fetter, 2001, p 129). For the upper stratigraphic portion of the Troublesome Aquifer, this relation allows close estimation of depth to water table when well control is not nearby. Groundwater gradients in the Lower Troublesome are more difficult to determine due to the dearth of wells screened there. As stated earlier, current interpretations indicate that the Upper and Lower Troublesome are hydraulically connected and unconfined. They are classified as a Type II aquifer (**Fig 1-5, Appendix-Fig A3-2a, A3-2b**). The aquifer-wide gradient in deeper portions of the aquifer is interpreted to be the same as noted above at approximately 2.7 percent.

The interim manual contour map (**Fig 2-1**) is similar to a previous 1997/1998 BBA water-table elevation map of the aquifer water table. Although the BBA map was based on only 33 wells available at that time, both maps show similar water-table contours with the current 2022 map illustrating much more detail and elongation of the contour lines in the east-west direction.

These manually generated contours are used as input, along with point data from all wells, to create a more rigorous computer-generated map implementing commonly used gridding techniques (“Surfer” mapping application, Golden Software, LLC ‡). This effort resulted in a map tied more closely to well data, providing finer details in the Final Potentiometric / Water-Table Elevation Map (**Fig 2-3**).

‡ Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the authors.

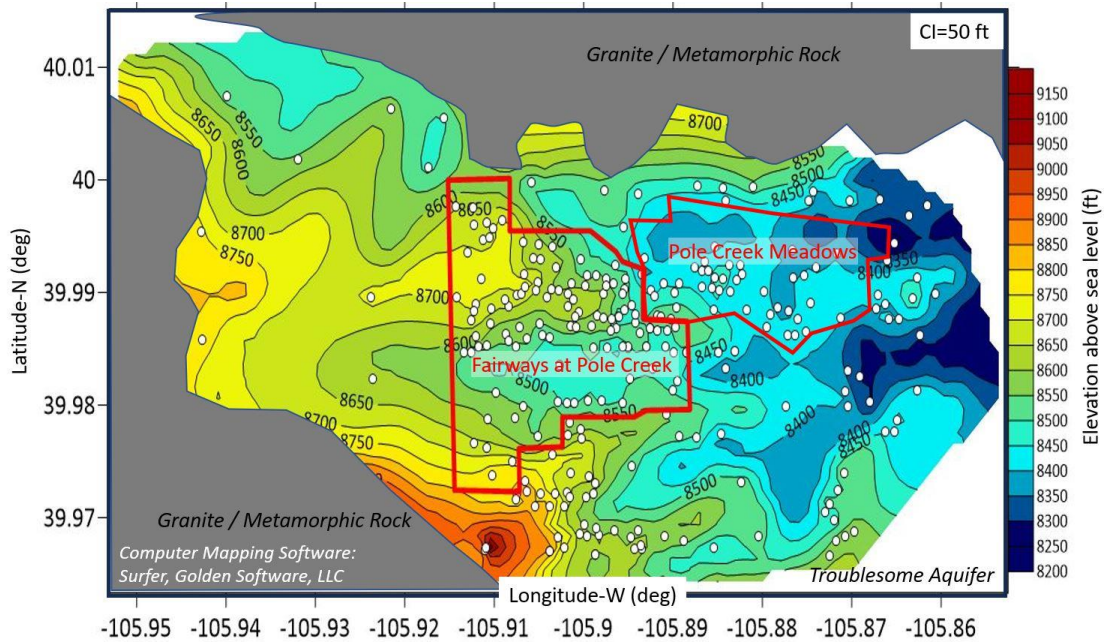


Figure 2-3. The Final Potentiometric Map (Water Table Elevation Map) with computer generated contours based on all 270 wells precisely located.

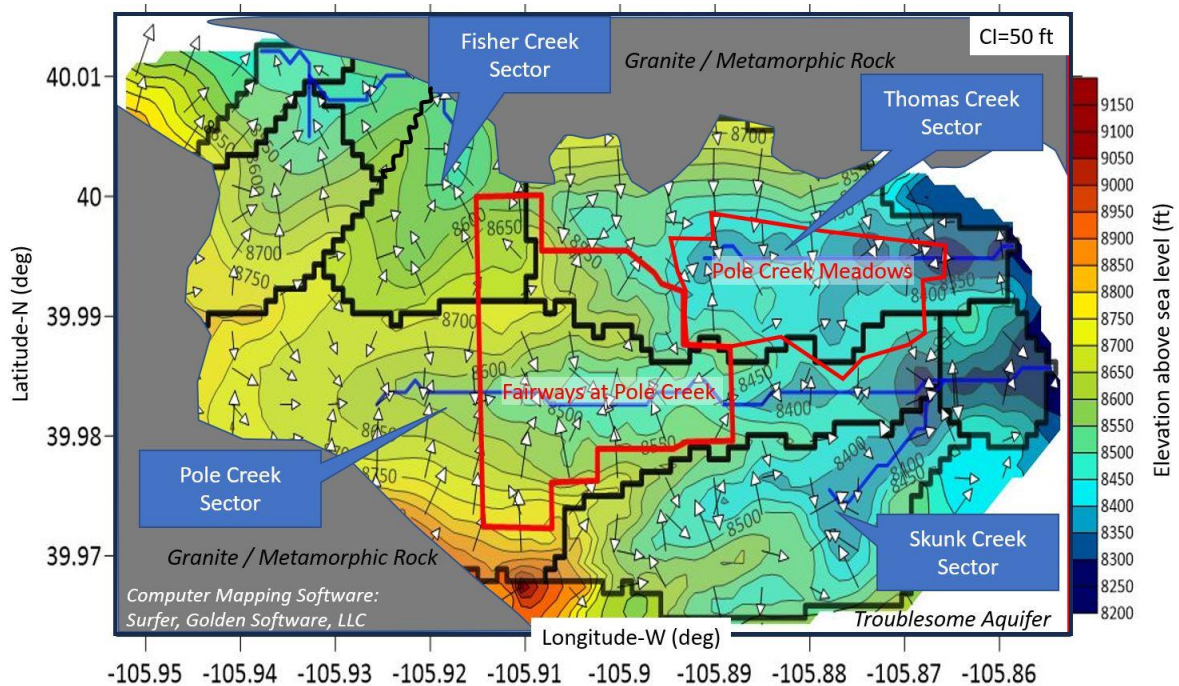


Figure 2-4. Potentiometric map with watershed sub-basins. Five main sectors within the study area are delineated by heavy black lines. The vector arrows represent the direction and relative hydraulic gradient of water flow within the aquifer.

The Final Potentiometric Map is subdivided into five aquifer sub-basins across the study area, three within the Fairways Development: Pole Creek, Thomas Creek and Fisher Creek (**Fig 2-4**). The Pole Creek Meadows Development resides primarily in the Thomas Creek sub-basin. This map also displays water-flow vectors within each of the watershed sub-basins. The vectors indicate direction, and the length of vectors indicate the relative hydraulic gradient of groundwater flow through the aquifer. The water flow through these sub-basins is greatly affected by aquifer recharge and discharge to streams (**Section 3.2**). This map can also be used to back-track the source of potential contamination within the aquifer. Delineation of aquifer sub-basins and water flow between them are somewhat subjective and could be improved with more rigorous numerical flow modeling. The Final Potentiometric Map (**Fig 2-3**) and associated cross-sectional profiles (**Fig 2-5a, 2-5b**) depict a water-table level closely matching the surface topography with two prominent ridges and adjacent lows traversing E-W through the Greater Pole Creek Basin.

Complementary maps and profiles, including depth to water-table below land surface (**Fig 2-6**), depth to upper-most sand aquifer (**Appendix-Fig A2-2**) and three cross-sectional profiles (**Fig 2-5a, 2-5b**), provide greater detail for anomalous faulted areas in the aquifer.

2.2 Aquifer Segmentation – Effect of Water Flow to Wells

A water-table ridge within the Fairways Development is disrupted by abrupt changes in water-table elevations. These discontinuities may be a result of minor faults that either restrict or provide conduits for flow, creating small, segmented ridges and troughs in the water table (Area of Interest, **Fig 2-6, 2-7a-c**). Inferred linear faults based on obvious surface topography and stream orientations have been noted on the surficial geologic map (USGS GQ-1224, Taylor, 1975, **Fig 1-4a**). Smaller surface topographic variations (**Fig 2-7c**) along with corresponding discontinuities in the subsurface potentiometric map (**Fig 2-7a**), water-table-depth map (**Fig 2-7b**), upper-sand depth map (**Appendix-Fig A2-2**), and depth profiles (**Fig 2-5a, 2-5b**) all suggest smaller faults within the aquifer. Fault interpretation is approximate because precise positioning cannot be determined based on current well data and geological information.

These anomalous, perhaps faulted, areas coincide with three wells that stopped producing water in sufficient quantities and were replaced (“failed/replacement” wells) and one “major workover” well (**Fig 2-7a-c**). All these problematic wells are in close proximity to each other and are the only such wells within the entire study area (**Table 2-1**). They are not likely random occurrences and are likely due to abnormal local variations in the aquifer.

Faults displace two or three targeted water-producing sand stringers in this area, all of which are relatively thin (average 4.7 ft thick) (**Table 1-1a**). These are separated by low conductivity massive silt layers that, because of the platy nature of silt particles, restrict vertical flow to an even greater extent.

The faults may isolate segments of sand and therefore reduce transmission of water to a pumped well (Fig 2-8, blue dashed line, Bense, and others, 2013, p 172-175) or may provide conduits for flow from one sand stringer to another (Fig 2-8, dark red dashed line). Faulted zones may be more susceptible to greater changes in water levels throughout the year, especially if zones correspond to greater domestic water use as evidenced by the relative high density of wells within the Fairways Development.

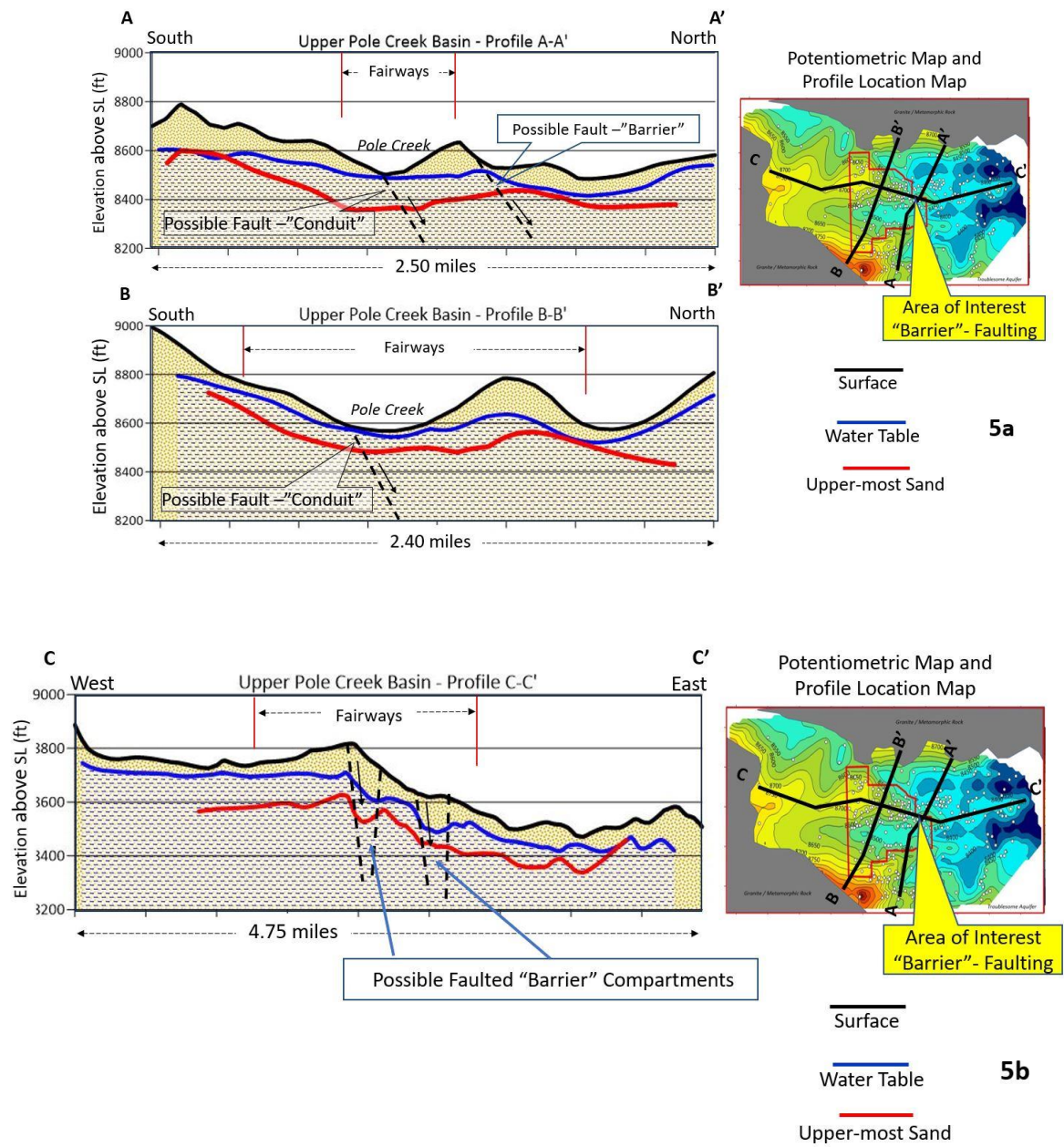


Figure 2-5a, 2-5b. Geologic profiles that traverse the project area (transects shown on map) depict the relation between the surface, water-table level and the uppermost saturated sand encountered in the wells. Note the “Area of Interest” corresponds to abrupt changes in the water table and associated possible “barrier” faults shown on profiles A-A’ and C-C’. “Conduit” faults coincident on the surface with Pole Creek (Fig 1-4a) are depicted on profiles A-A’ and B-B’.

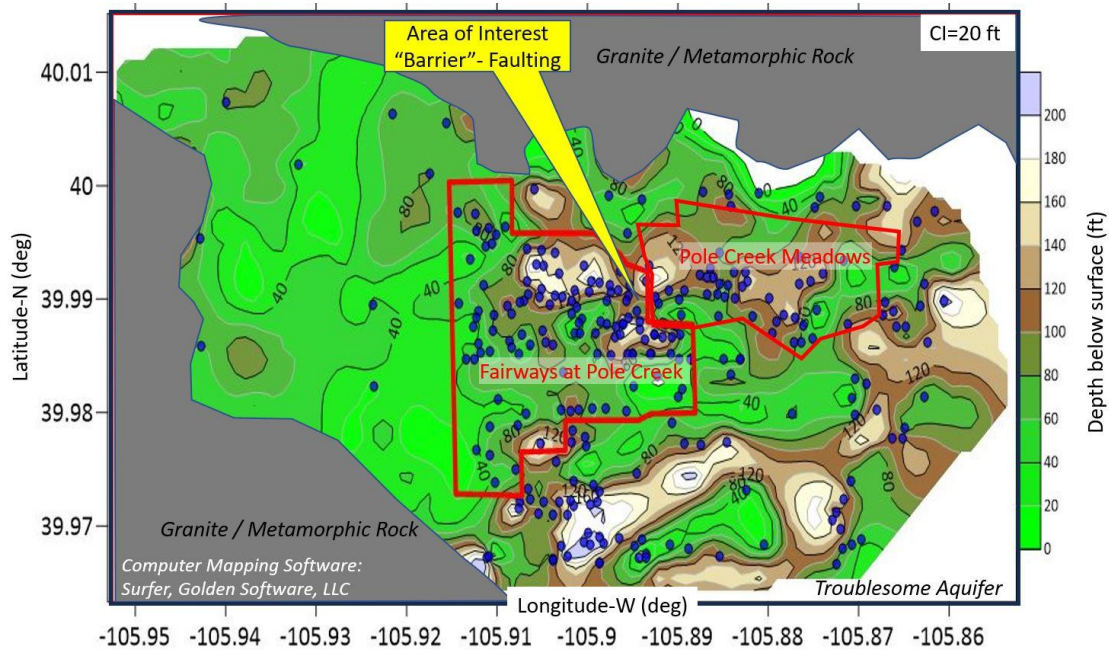


Figure 2-6. Depth of the water table beneath land surface, in feet. “Area of Interest” features abrupt changes in water table depths and infers “barrier” faulting that may partially restrict aquifer water flow.

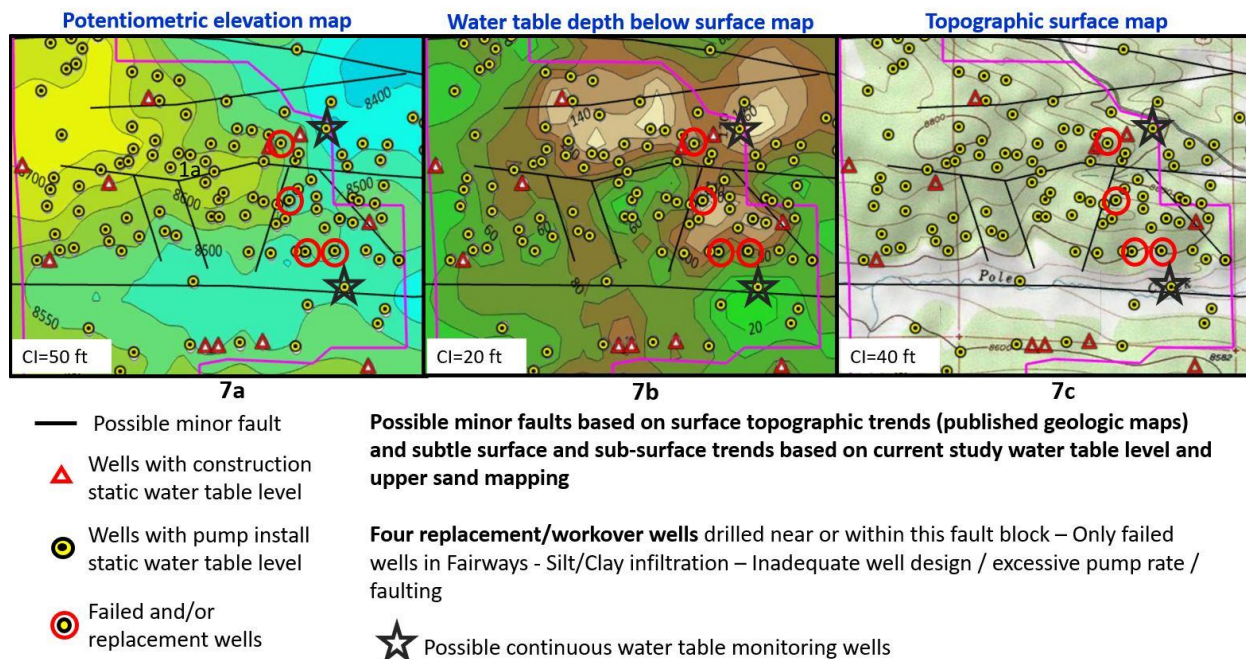
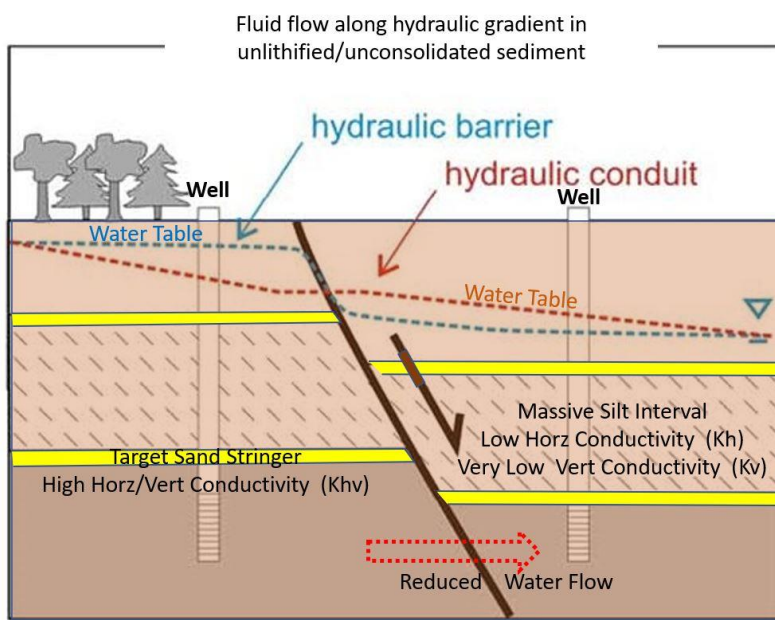


Figure 2-7a, 2-7b, 2-7c. Expanded maps from “Area of Interest” (Fig 2-5a, 2-5b, 2-6) depict the potentiometric surface (7a), depth to water table (7b) and surface elevation (7c). All maps show inferred faults based on abrupt change in the potentiometric level or gradient, depth of the water table, and dominant linear topographic trends as well as subtle surface topography variations. Four replacement wells are noted, all within close proximity and within compartmental fault blocks. The locations of possible continuous water-table monitoring wells are depicted.



Modified from Bense, and others, 2013 – Fault Zone Hydrogeology

Figure 2-8. A generalized aquifer fault model demonstrates how thin sand stringers encased in massive thick silt sections are displaced along faults, potentially affecting water flow. The offset of the sand against the silt intervals may cause abrupt change in water-table levels on either side of the fault. The water-table level shown in blue is representative of a “barrier” fault influence whereas the water-table level shown in red is the result of enhanced flow (reduced water-table slope) and is considered a “conduit” to water flow.

Discussions with the drilling contractor who replaced the problem wells indicate these wells failed due to massive silt infiltration into the well bore, which may be due to well construction and excessive pumping detailed in **Section 4.1**. Aquifer sediment immediately adjacent to a fault may be associated with reduced average grain size or loose grain compaction due to fault movement, thus making the well more susceptible to fine-grain movement adjacent to and through the well screen.

2.3 Time Variant Water-Table Changes

Even though there are sporadic years of increased precipitation, there is a long-term drought trend within the Fraser Valley (**Section 3.1**). This trend prompts concern about the Upper Troublesome Aquifer’s ability to supply sufficient water to meet future domestic needs. To get a first approximation of long-term fluctuations of aquifer water quantity since onset of the recent drought (ca 1997), an assessment of water-table fluctuations was undertaken using domestic well data.

Static water-table elevations were derived from water-level measurements made during pump installations. These measurements from 243 wells were then sorted into two groups based on dates of installation: those prior to 2010, and 2010 through 2022. Both groups of pump-installation water-level elevations were cross plotted against associated land-surface elevations (**Fig 2-9**) along with simple linear regression trends. The pre-2010 and post-2010 regressions that are derived from 161 and 82 wells, respectively, provide the average slope of the water-level elevation relative to land surface elevation across the study area. These regression slopes approximate the hydraulic gradient across the study area. Both period regressions show very similar slopes with no definitive variations in the data distribution pattern. Therefore, these observations are indicative of no discernable change in the recharge rate and water volume of the Upper Troublesome Aquifer. The minor variations from year to year are normalized over the approximate 12-year period.

Six replacement/workover wells were drilled in the study area with replacement wells drilled immediately adjacent to the original well (**Table 2-1**). Because water-level measurements were made at the times of pump installation for both the original and the replacement well, these point measurements provide the best assessment for long-term water-level changes in the aquifer. Three of the four wells within the Fairway “Area of Interest” (**Fig 2-7a-c**) show minimal change in water levels over periods of 15 years (**Table 2-1**), thus indicating virtually no drought-related change in the aquifer water volume in the central portion of the study area.

Although there was substantially less precipitation during the longer-term drought trend, data indicate that aquifer recharge was sufficient to offset increasing groundwater use in the study area as evidenced by virtually no net water depletion of the aquifer. Details are outlined in **Section 3.7**.

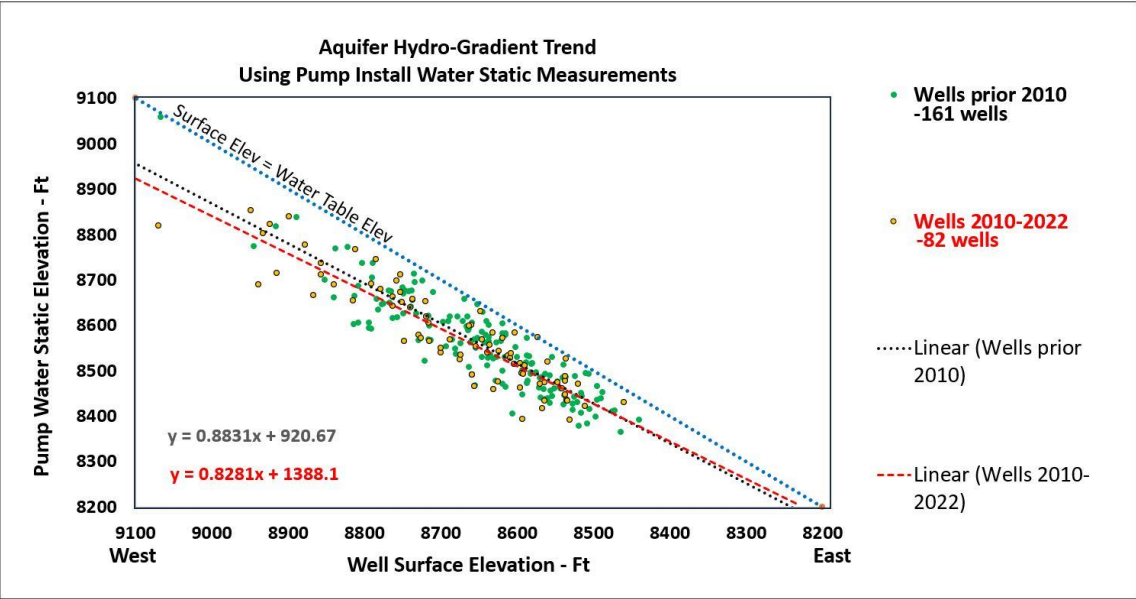


Figure 2-9. Water-level elevation in wells is relative to land-surface elevation during two periods: prior to 2010 and from 2010 to 2022. Linear regressions for the two groups of data are depicted.

Table 2-1. Well data associated with original and replacement wells with water table level differences and duration between drilling of the wells.

Original and Replacement Wells - Long Term Time Variation of Water

Permit	Elev	Sect	Q40	Q160	Pump Inst Date	Diff Yrs	Static Level-Ft	Diff Level-Ft	Filing Lot	Development
57533-F	8595	4	NE	SE	4/8/2004		99		1 10	Fairways at Pole Creek
57533-F-R	8594	4	NE	SE	7/23/2019	15.3	98	-1	1 10	Fairways at Pole Creek
61174-F	8583	4	NW	SE	11/1/2005		90		1 7	Fairways at Pole Creek
61174-F-R	8583	4	NW	SE	6/10/2006	0.6	86	-4	1 7	Fairways at Pole Creek
61620-F	8656	4	SW	NE	9/2/2005		188		1 43	Fairways at Pole Creek
61620-F-R	8656	4	SW	NE	7/14/2012	6.9	188	0	1 43	Fairways at Pole Creek
60884-F	8646	9	SW	SE	9/24/2004		15			SHEEP MOUNTAIN RIDGE ESTATES
60884-F-R	8646	9	SW	SE	8/27/2013	8.9	16	1		SHEEP MOUNTAIN RIDGE ESTATES
61105-F	8716	9	SE	SW	11/1/2004		94			SHEEP MOUNTAIN RIDGE ESTATES
61105-F-R	8716	9	SE	SW	12/22/2011	7.1	110	16		SHEEP MOUNTAIN RIDGE ESTATES
61321-F	8945	9	SW	SW	4/6/2005		170			SHEEP MOUNTAIN RIDGE ESTATES
61321-F-R	8949	9	SW	SW	11/6/2013	8.6	76	-94		SHEEP MOUNTAIN RIDGE ESTATES

2.4 Aquifer Water-Table Monitoring – Proposed Additional Wells

Long-term continuous water-table monitoring is necessary to draw more reliable conclusions related to changes in aquifer volumes and sustainability. Currently there are no monitoring wells for determining continuous water-table levels in the study area. Two possible well-monitoring locations are depicted for consideration (**Fig 2-7a-c**). Both are non-residential wells where added water-level sensors could be connected to remote sensing and communication equipment to provide near-real-time data. Both wells are within the Fairways Development area. The southernmost well is on the golf course and is an unused deep irrigation well that extends several hundred feet into the Lower Troublesome. This well appears to be within the non-faulted area near Pole Creek and would be an excellent benchmark reference well for aquifer variations in the Troublesome. The northern proposed monitoring well is the Fairways front-entrance irrigation well. This well is located on a topographic high and near or within the fault deformation area.

Collecting data from both wells would allow time-series analyses and assessment of the Troublesome from both seasonal and daily water-table-drawdown effects. Additionally, aquifer chemical dye trace surveys and analyses could help define aquifer compartmentalization. Implementation would be based on location approval, funding, permitting and logistical issues associated with installation and monitoring.

3 - Pole Creek Water Budget and Troublesome Aquifer Viability

3.1 - Watershed Precipitation

Past USGS hydrology reports for Fraser Valley (Apodaca and Bails, 1999, p 4; Bauch and Bails, 2004, p 3) have referenced pre-1997 average precipitation in the Fraser Valley watershed as 20-40 in/year (lower and higher elevations respectively). The BBA Hydrology Report (1997-98) estimated 21 in/year in the Greater Pole Creek Basin watershed. Since 2000, the inter-mountain western US and the Colorado River Drainage Basin in Colorado has experienced a substantial decrease in annual precipitation and experienced moderate and periodic exceptional drought conditions (University of Nebraska, 2023 – Drought Monitor: **Fig 3-1**). The Fraser Valley in Grand County, Colorado, which includes this 2022 study area, has also been subjected to this drought trend. Using data from Colorado State University (2022), yearly precipitation amounts from two weather stations in the county (one in Fraser Valley, one in Grand Lake 22 miles to the north) have been tabulated and graphed (**Fig 3-2**). (All extracted historical precipitation data for these weather stations used for these analyses are tabulated and available via USGS Science Data Catalog, Rosenberry and Stoughton (2024)).

Even with considerable year-to-year fluctuations, there is a clearly decreasing statistical trend. Annual precipitation has decreased to approximately 13 in/year from 1997 to 2022, a reduction of nearly 38 percent compared to the beginning of the trend. If the trend continues, by 2035 the annual precipitation will be approximately 10 in/year (greater than 50% decrease).

Average precipitation varies greatly over the Fraser Valley watershed, with the largest amounts associated with snowpack accumulations along the high surrounding mountain ranges and the smallest amounts in the central valley. The Fraser Valley Watershed Precipitation Map (Colorado State University, 2022) (**Fig 3-3**), based on data collected prior to 1984, demonstrates these variations. Average pre-1984 precipitation amounts for each sub-watershed area, including those associated with the Greater Pole Creek Basin, can be estimated from the map. This pre-drought map demonstrates that average precipitation in Fraser was 19 in/year. For comparison, the most recent 2022 Fraser weather station data indicate an average of 13 in/year. The best-fit regression line of Fraser precipitation shown in **Fig 3-2** also indicates a precipitation amount of approximately 13 inches for 2022. To estimate a precipitation distribution across the Greater Pole Creek Basin for 2022, a multiplier of 0.684 based on the ratio of 13/19 was applied to the pre-1984 map. Assuming the whole watershed is affected in the same manner, the average precipitation taken from the map of each sub-watershed sector can be revised to reflect 2022 precipitation inputs. The map-derived estimates of 2022 distributed-precipitation amounts are tabulated and displayed in **Tables 3-1a and 3-1b** respectively. The final weighted-average precipitation of the combined sub-watershed areas within the Greater Pole Creek Basin is nearly 13 in/year, as shown in the red rectangle. Precipitation varies between the higher- and

lower-elevations portions of the sub watersheds sectors and estimates are provided for both sectors with the weighted average calibrated values shown on the map (**Fig 3-4a**). Other current precipitation estimates of watershed areas within the valley can be derived in a similar manner.

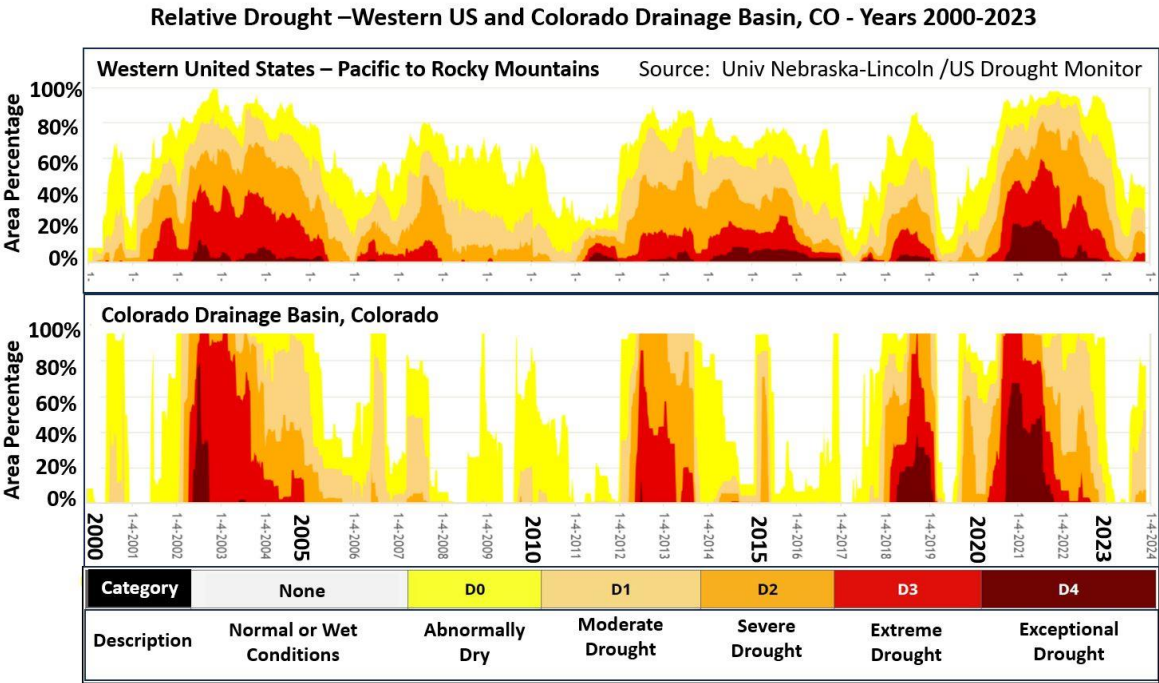


Figure 3-1. Drought intensity within the Western US and the Colorado River Drainage Basin in Colorado from years 2000 to 2023. The drought intensity is determined as a percentage of area within a region with colors indicating drought severity.

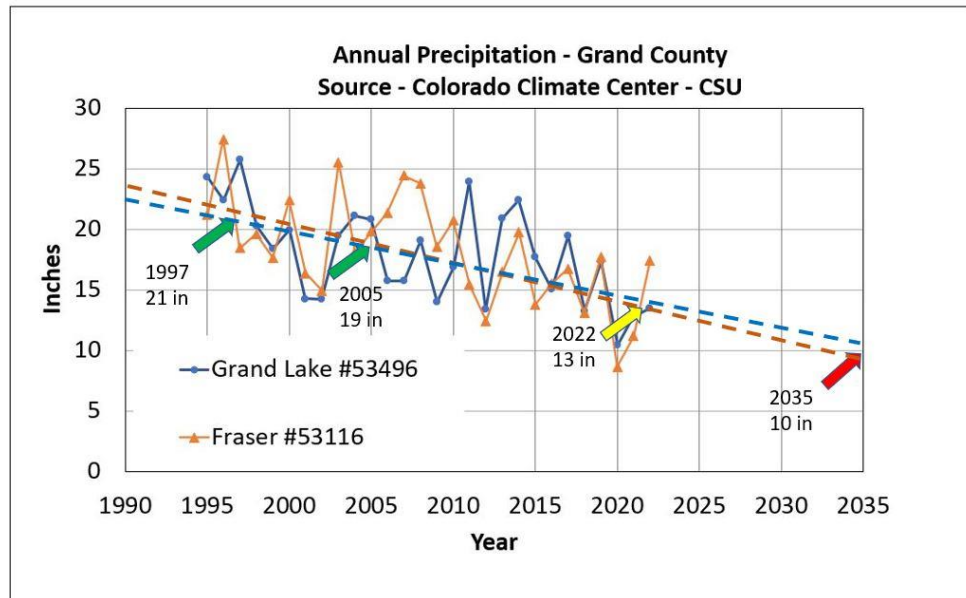
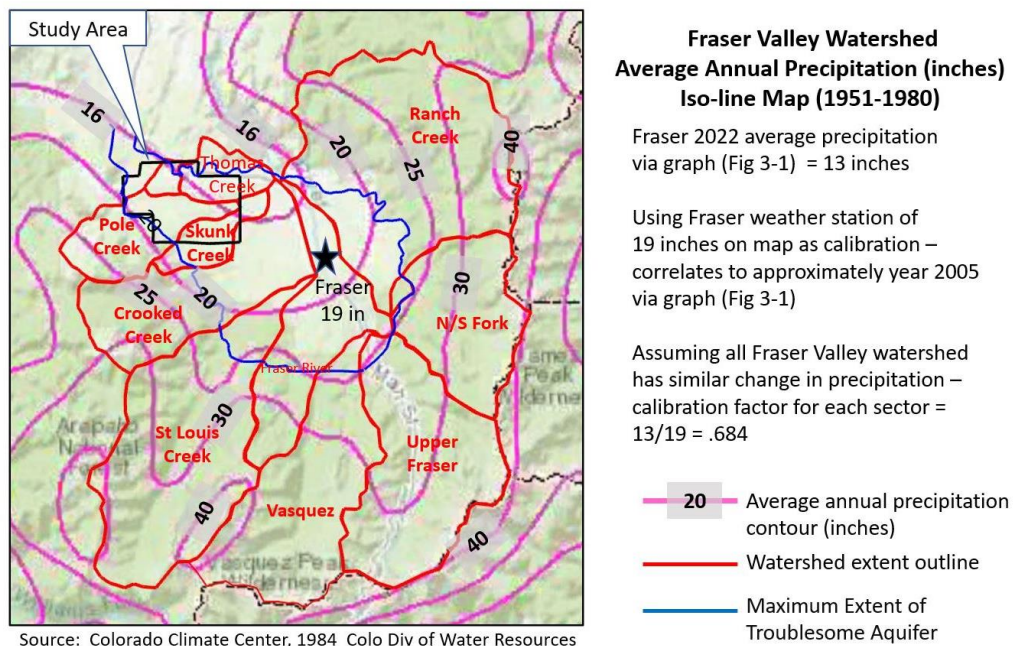


Figure 3-2. Annual precipitation trend of Grand Co, Colorado is based on data from two weather stations (USGS Science Data Catalog, Rosenberry and Stoughton (2024)). Graph demonstrates an average 38 percent decrease in precipitation over a 25-year period (1997-2022).



a.

Figure 3-3. The pre-1984 precipitation map illustrates the variance and distribution of precipitation over the Fraser Valley watershed. The sub-basin watersheds are outlined in red, and the extent of the Troublesome Aquifer is

outlined in blue. The map and the Fraser weather station 2022 average precipitation serves as a basis for scalar calibration of other sub-basin watershed precipitation estimates and specifically within the Study Area.

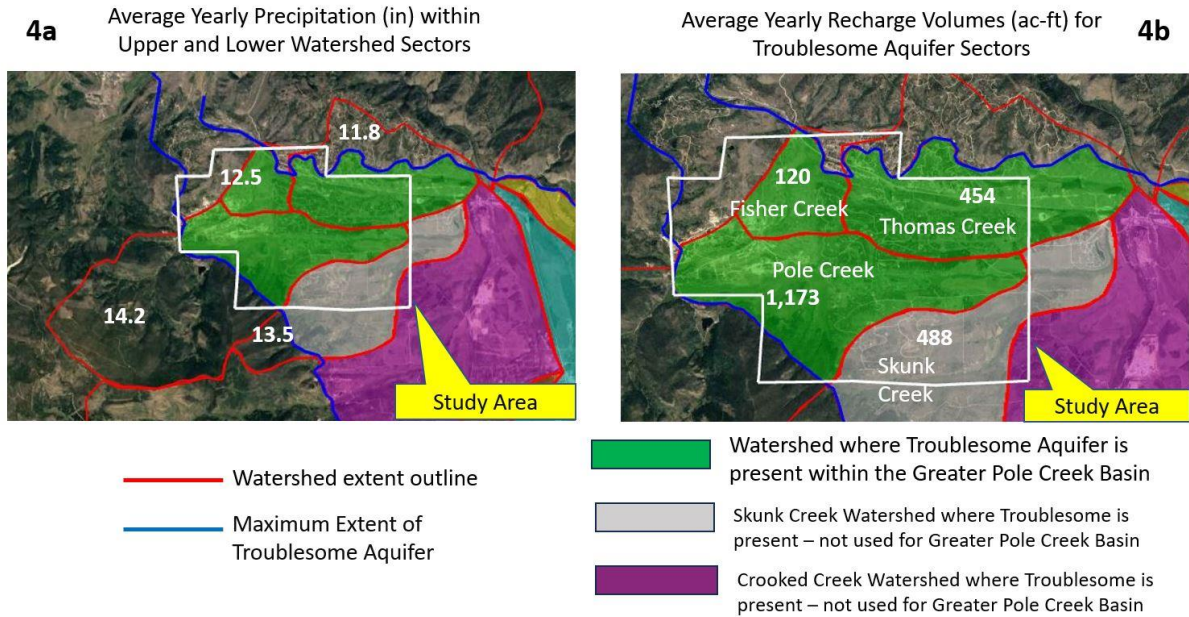


Figure 3-4a & 3-4b. Map of sub-watershed basins outlined in red with annotated calibrated average annual precipitation (4a). The average aquifer recharge volume map (4b) shows derived net groundwater recharge volumes for each sub-watershed basin, with the net volumes annotated on the map based on 15 percent recharge rate. Colored segments represent Troublesome Aquifer distribution within each sub-watershed basin with the blue line indicating the extent of the Troublesome within the Fraser Valley.

Table 3-1a, 3-1b, 3-1c, 3-1d, 3-1e. Data table denotes the map-derived estimated annual precipitation within the sub-watershed basins (1a and 1b respectively). The area sectors within each sub-watershed basins are broken down into higher and lower elevations segments (Upper and Lower respectively). Associated areas for each sub-basin watershed are tabulated (1c) with the resultant gross water volumes (1d). Estimated net recharge volumes for 10, 15 and 20 percent of gross water volumes are depicted (1e) with the most likely 15 percent recharge rate volumes outlined in red.

1a

Map Based Precipitation within Watersheds (in)			
Watershed Sector	Precip Upper	Precip Lower	Wt Average
Pole Creek	21.6	19.4	20.8
Thomas Creek	17.2	17.2	17.2
Fisher Creek	18.3	18.3	18.3
Average	19.0	18.3	18.8

1b

Calibrated Precipitation within Watersheds (in)			
Watershed Sector	Precip Upper	Precip Lower	Wt Average
Pole Creek	14.7	13.3	14.2
Thomas Creek	11.8	11.8	11.8
Fisher Creek	12.5	12.5	12.5
Average	13.0	12.5	12.9

1c

Watershed and Troublesom Aquifer Acreage			
Watershed Sector	Acreage Upper	Acreage Lower	Acreage Total
Pole Creek	4,346	2,244	6,592
Thomas Creek	1,075	2,003	3,078
Fisher Creek	128	640	768
Grt Pole Crk Total	5,549	4,887	10,438

1d

Annual Water Available from Watersheds			
Watershed Sector	Ac-ft Upper	Ac-ft Lower	Ac-ft Total
Pole Creek	5.34E+03	2.48E+03	7.82E+03
Thomas Creek	1.06E+03	1.97E+03	3.03E+03
Fisher Creek	1.34E+02	6.68E+02	8.02E+02
Total for Greater Pole Creek Sector			1.16E+04

1e

Estimated Annual Recharge Volumes (Ac-ft)			
Watershed Sector	Lower Limit 10%	Most Likely Volume 15%	Upper Limit 20%
Pole Creek	782	1,173	1,564
Thomas Creek	303	454	605
Fisher Creek	80	120	160
Total	1,165	1,747	2,330

3.2 - Aquifer Recharge

The gross volume of water available for annual aquifer recharge (acre-ft) (**Table 3-1d**) is determined by multiplying annual precipitation (**Table 3-1b**) by the area (**Table 3-1c**) of each sub-basin. Most of the annual precipitation runs off into streams and rivers and a sizable portion is lost to evaporation and plant absorption (transpiration). Aquifer recharge, the percentage of precipitation that makes its way into the aquifer, is affected by topography, rock or sediment type, vegetation, temperature, humidity, and other factors. Estimates of aquifer recharge often include substantial uncertainty. Numerous studies regarding aquifer recharge in similar environments have been rigorously reviewed and summarized (Heath, 1983; Marovich and others, 2019).

The BBA (1997/1998) Hydrology Report indicated a “rule of thumb” estimate of 5-10 percent of precipitation contributes to aquifer recharge. A subsequent Fraser Valley hydrology modeling study by Aigler & Ge (2012, p 7) assumes a 2.95 in/year (75 mm/year) surficial recharge rate within the lower portion of the Greater Pole Creek Basin watershed. This same study also reports precipitation variation of 14-35 in/year (350-900 mm/year) mostly correlated with elevation within the entire watershed. The pre-1984 precipitation map (**Fig 3-3**) and calculated mid-range precipitation value of 19 in/year (**Table 3-1a**) resides within this range of precipitation. The calculated recharge rate as a function of precipitation (2.95/19.0) equates to an estimated 15.5 percent. Using the assumed surficial recharge rate and variation in precipitation, the range of overall recharge rates as a function of precipitation varies from 8-21 percent. This current study assigns a recharge rate range of 10% (lower limit with lower probability), 15% (most likely with approximately 50% probability), and 20% (upper limit with lower probability) (**Table 3-1e**) for comparison purposes. **Figure 3-4b** depicts the three watershed sub-basins and their associated recharge volumes assuming a 15 % recharge rate. The derived total

recharge volume of 1,747 acre-ft, based on 15% recharge rate for the upper portion of the Troublesome Aquifer within the Greater Pole Creek Basin, is used for current (2022) water balancing/accounting discussed later in this section.

3.3 - Aquifer Hydraulic Properties

Flow through the Alluvial and Troublesome Aquifers is controlled primarily by hydraulic conductivity of the various sediments that make up the aquifers and the hydraulic gradient. Hydraulic gradient varies over time as the difference in head that drives flow changes seasonally and in response to groundwater-recharge events. However, hydraulic conductivity (K) can often be considered a fixed property of the porous media. K is the relative resistance to flow of fluid/water through a porous media, including aquifers. It is a function of both the density and temperature of the fluid, values that change very little in most aquifers and can generally be considered constant, and the physical geometric nature of the sediment grains. K can be determined by several methods including well drawdown pumping tests, single-well “slug” tests, sediment grain-size distribution, laboratory measurements, analytic calculations, and numerical simulations. Chemical tracer surveys between wells can also provide insight to the rate of aquifer flow. Well drawdown pumping tests provide the highest level of confidence for determining aquifer parameters but are rare for the Fraser Valley. Most were conducted in municipal wells completed within the Alluvial Aquifer and documented via private reports.

The Troublesome Aquifer covers the entire Fraser Valley basin within the study area (**Fig 3-5a**) and is truncated along the surrounding higher basin margins adjacent the crystalline rock mountains. The upper portion of the Troublesome is overlain by the Alluvial Aquifer in the central portions of the valley (**Fig 3-5b**). As mentioned earlier, the uppermost Troublesome Aquifer is silt dominated with several stringers of sand with total interval thickness ranges between 400-500 feet. Despite being composed mostly of silt, it is the main source of domestic water consumption through homeowners’ wells along the margins of the valley. The younger Alluvial Aquifer is dominated by sand (**Fig 3-5b**). It varies from 0 to approximately 140 feet in thickness (Bauch, 2004) and is the main source of municipal water in the central valley.

Aigler and Ge (2012) provide analyses of hydraulic properties from a consolidation of key well tests, municipal Alluvial Aquifer wells near Fraser, and test wells 4.3 miles further west penetrating the Upper Troublesome Aquifer (**Fig 3-5a, 3-5b**). In addition, lab measurements, and calibrated numeric aquifer flow simulations and sensitivities have been derived using the USGS modeling software (MODFLOW). Two reference-well drilling logs, Type A & Type B (**Fig 3-6**) with locations shown on the maps (**Fig 3-5a, 3-5b**), represent the type of sediment encountered within the two aquifers. These are the same wells referenced by Aigler & Ge (2012) for their detailed investigations. The drilling log for Type A well (**Fig 3-6**) in the Upper Troublesome Aquifer has a small net/gross (N/G) sand thickness of 3% and approximate measured average K of 0.3 ft/day (1E-4 cm/sec) whereas the Alluvial Aquifer, Type B log, demonstrates a N/G of 35% and K of 284 ft/day (1E-1 cm/sec). These K values indicate the resistance to water flow is 1000 times greater in the Upper Troublesome Aquifer than in the Alluvial Aquifer.

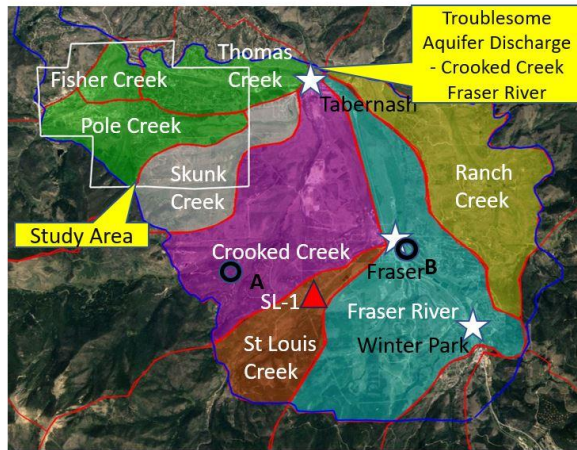
Drawdown in response to pumping the Upper Troublesome well Type Well A is much larger and the well recovers much more slowly than the Alluvial Type Well B.

Based on a summary of the pertinent literature, K , of the Alluvial Aquifer averages 108 ft/d and K of the Upper Troublesome Aquifer averaging 1.5 ft/day (**Fig. 3-7, Table 3-2a, Table 3-2b**). Resistance to vertical water flow is nearly an order of magnitude greater in the Upper Troublesome than in the isotropic nature of the Alluvial Aquifer. In addition, larger anisotropy, the ratio of K along a horizontal axis to K along a vertical axis, is evident in the silt dominated sediment. Anisotropy in the Upper Troublesome is 10, largely due to the nature of the flat lying silt/clay sediment grains (**Fig 3-6, 3-8, Aigler and Ge, 2012**).

Estimates for K can also be determined if values for transmissivity (T) are available. T is the product of K and aquifer thickness (b) ($T = K \times b$) and is a hydraulic property related to aquifer water extraction. The Upper Troublesome Aquifer has much lower transmissivity than the Alluvial Aquifer. An estimated T for the Upper Troublesome has been reported as 5,000 gal/day/ft (Apodaca, 1999; Bauch, 2004) and has been used in this study for recharge estimates using the average 304 ft saturated thickness. T of the Alluvial Aquifer is approximately 12,000 gal/day/ft (Apodaca, 1999 / Bauch, 2004) but with a substantially smaller saturated thickness of less than 105 feet (**Table 3-2a, 3-2b**).

An extended Fraser Valley basin-wide evaluation of Upper Troublesome associated with this study (**Appendix-Table A1-3a**) resulted in an average saturation thickness of 378 feet. When combined with T of 5,000 gal/day/ft, a hydraulic conductivity (K) of 1.8 ft/day was derived. For the Alluvial Aquifer, an average saturated thickness of 46 feet was calculated from the isopach/thickness maps (Bauch and Bails, 2004). Using T of 12,000 gal/day/ft, a K estimate of 34.9 ft/day was derived.

The high silt content and thin stringers of sand present in the Upper Troublesome Aquifer may be problematic for moderate to high rates of water production in domestic wells. An internal Colorado Division of Water Resource memo (Graham, 1998) indicates moderate concern of “very low transmissivity” for the Upper Troublesome Formation. The same memo cites “anomalously high drawdowns” during aquifer pumping tests, indicating slow aquifer water replacement flow. The report also states that, “lack of replacement wells suggests domestic wells can sustain low yields for some time.” Since the release of that memo, three domestic wells have been replaced, all within close proximity to an area of apparent minor faulting, as described earlier (**Section 2.2**).

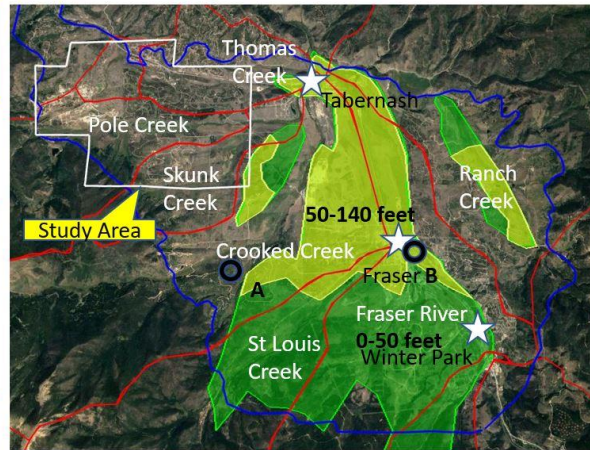


**Fraser Valley Watershed Basins –
Upper Troublesome Aquifer Sectors**

5a

- Water source for most domestic wells
- Producing wells predominately along margins of the valley
- 400-500 feet thickness / 45 sq mi

▲ USGS surface stream gage station



**Fraser Valley Watershed Basins –
Near Surface Alluvial Aquifer Distribution**

5b

- Water source for domestic wells/municipalities
- Producing wells predominately in central valley
- Up to 140 feet thickness / 23 sq mi

● Type Wells – A & B – Shown on Figure 3-6

Figure 3-5a, 3-5b. Distribution maps of the Upper Troublesome Aquifer (**5a**) and Alluvial Aquifer (**5b**) within the Fraser Valley. Each of the colored sections in **5a** represents the Troublesome Aquifer within watershed sub-basins with associated drainage surface streams. The colored green and yellow sections in **5b** illustrate the distribution of the Alluvial Aquifer and the estimated thickness. This Aquifer is present predominantly along the Fraser River and tributaries. Only the Troublesome is within the Study Area. Two key wells annotated on each map are selected for extended studies for aquifer hydraulic properties, type well A for the Troublesome Aquifer and type well B for the Alluvial Aquifer.

Type Well - A

Crooked Creek Ranch (CCR)
Test Well - 1999
T1S R76W Sec 21 SE/NE

5. GEOLOGIC LOG:		
Depth	Description of Material (Type, Size, Color, Water Location)	
0	6	Topsoil
6	9	Decomposed (Boulders)
9	18	Gravel & clay (sealed) xx
18	24	Brown Clay Water Table at 25 ft
24	48	Clay & Sandstone
48	86	Brown clay
86	90	White sandstone 4 ft xx
90	132	Clay and sandstone
132	188	Brown clay
188	238	Clay & sandstone
238	268	Brown clay
268	272	Sandstone 5 ft xx
272	302	Brown clay

Net sand = 9 ft

Pumping Test – Nearby Well
Pump Rate = 5 gpm / Test Length = 1 hr
Drawdown = 29-200 ft = 171 ft

Upper Troublesome Aquifer - Anisotropic
Kh (horizontal) = 0.3 ft/day (1E-4 cm/sec)
Kv (vertical) = 0.1 ft/day (5E-5 cm/sec)

Alluvial Aquifer

Sat Int
Net/Gross=
47/135 = 34.8%

U Troublesome
Aquifer

Sat Int
Net/Gross=
9/277 = 3.2%

Type Well - B

Winter Park Ranch (WPR)
Municipal #7 Well - 1982
T1S R75W Sec 20 NE/SW

5. GEOLOGIC LOG:		
Depth	Description of Material (Type, Size, Color, Water Location)	
0-4'	Topsoil	Water Table at 3 ft
4'-17'	Glacial Deposit	
17' -58'	Siltstone	
58' -73'	Sandstone/siltstone	11 ft
73' -97'	Siltstone/sandstone	6 ft
97' -102'	Sandstone	5 ft
102' - 107'	Siltstone/sandstone	
107' - 132'	Sandstone	25 ft
132' - 138'	Siltstone	
138' - 165'	Siltstone/sandstone	
165' - 166'	Siltstone	

Net sand = 47 ft

Pumping Test
Pump Rate = 120 gpm / Test Length = 24.5 hr
Drawdown = 6 -63 ft = 57 ft

Alluvial Aquifer – Isotropic
Kh=Kv (hor & vert) = 284 ft/day (1E-1 cm/sec)

Figure 3-6. Geologic drilling logs of type wells (A and B) representative of the Upper Troublesome and Alluvial Aquifers respectively. Summary notations of aquifer hydraulic properties derived by Aigler and Ge, (2012) are shown for each type well. The Upper Troublesome Aquifer has much less sand (N/G) and is associated with much smaller overall (K) than the Alluvial Aquifer, thus water flow is much slower with greater effects on water well draw-down and recovery.

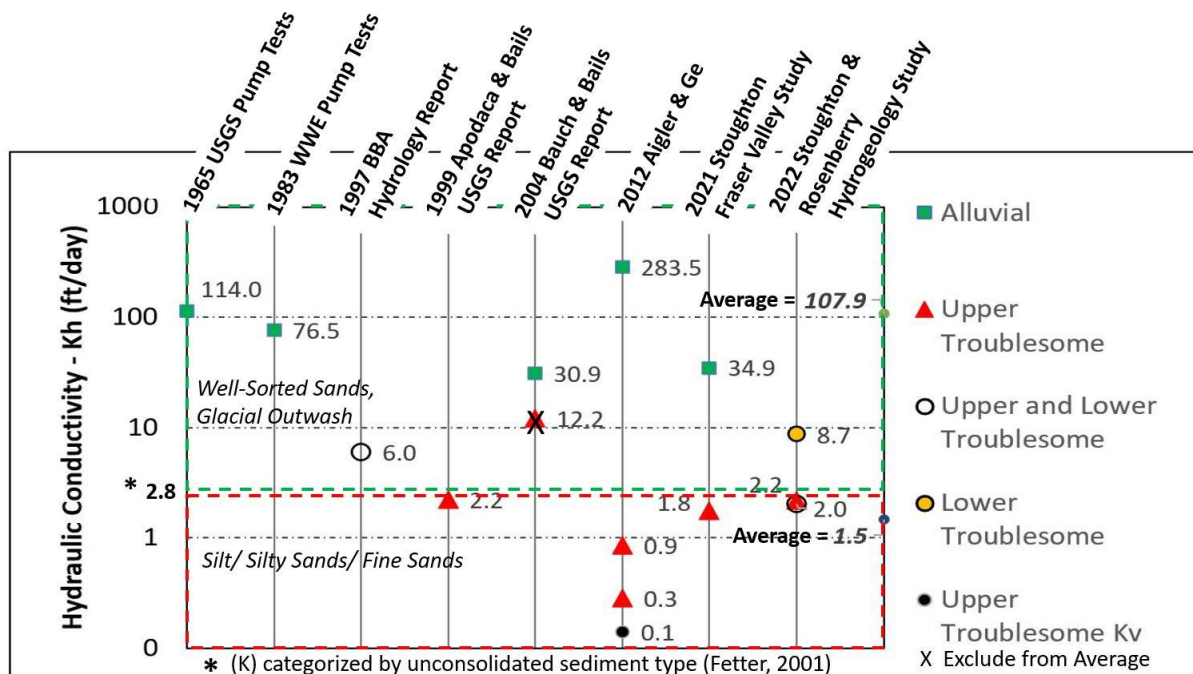


Figure 3-7. Comparative chart of hydraulic conductivity (K) values as documented by previous studies and current studies for both the Alluvial and Upper Troublesome Aquifers. The referenced K estimates are depicted chronologically from the earliest document (1965) to the values derived in this study (2022). Details of these referenced K estimates are provided in **Table 3-2a, 3-2b**. The representative sediment/conductivity groups are clearly separated and conform to those defined by Fetter, 2001. The averages for each grouping have been derived with the Alluvial Aquifer $K = 108$ ft/day ($3.8\text{E-}2$ cm/sec) and the Upper Troublesome with $K = 1.5$ ft/day ($5.2\text{E-}4$ cm/sec). Assuming equivalent hydraulic gradients, the water flows within the alluvial unconsolidated sediment flows approximately 74 times faster than the silt-dominated sediments within the Upper Troublesome.

Table 3-2a, 3-2b. Summary of aquifer hydraulic parameters quoted in previous reports and investigations and listed with this study's parameters. The previous reports include analyses of data from multiple sources and areas within the Fraser Valley for both the Alluvial and Upper Troublesome Aquifers. This study has attempted to consolidate all these known estimates and to derive a meaningful assessment and average of the key parameter of aquifer hydraulic conductivity (K) for these two aquifers (**Fig 3-7**).

Historical Data and Reference for Hydraulic Properties

2a

Ref #	Pub	Year	Source Author	Reference
1	Yes	1965	Wilson, W.W.	USGS Report wri03-4275 (2004)
2	No	1983	Wright Water Engineers, Inc	Environmental Earth Science Paper - Aigler & Ge (2012)
3	Yes	1999	Apodaca & Bails	USGS Report wri98-4255 (1999)
4	Yes	2004	Bauch & Bails	USGS Report wri03-4275 (2004)
5	Yes	2012	Aigler & Ge	Environmental Earth Science Paper - Aigler & Ge (2012)
6	No	2022	Stoughton	2022 Fraser Valley Aquifer Assessment
7	Yes	1999	Apodaca & Bails	USGS Report wri98-4255 (1999)
8	No	1999	Resource Engineering, Inc	USGS Report wri03-4275 (2004)
9	Yes	2004	Bauch & Bails	USGS Report wri03-4275 (2004)
10	Yes	2012	Aigler & Ge	Environmental Earth Science Paper - Aigler & Ge (2012)
11	Yes	2012	Aigler & Ge	Environmental Earth Science Paper - Aigler & Ge (2012)
12	TBD	2022	Stoughton & Rosenberry	2022 Greater Pole Creek Basin Hydrogeology Report
13	No	2022	Stoughton	2022 Fraser Valley Aquifer Assessment
18	Yes	2012	Aigler & Ge	Environmental Earth Science Paper - Aigler & Ge (2012)
24	TBD	2022	Stoughton & Rosenberry	2022 Greater Pole Creek Basin Hydrogeology Report
26	Yes	1997	Bishop-Brogden Assoc, Inc	G. C. Dept Planning and Zoning (1998)
30	TBD	2022	Stoughton & Rosenberry	2022 Greater Pole Creek Basin Hydrogeology Report

Historical Data and Reference for Hydraulic Properties

2b

T=Transmissivity / K=Hydraulic Conductivity / b=Saturated Thickness

Ref #	Aquifer	T (gpd/ft) Average	K (ft/day) Average	K (cm/sec) Average	b (ft) Average	Location	Method
1	Alluvial	12000	114.00	4.0E-02	105	Fraser Valley	Pump Test
2	Alluvial		76.54	2.7E-02		WPR- Municipal	Analytical
3	Alluvial	12000				Fraser Valley	Ref Previous Work
4	Alluvial	12000	30.85	1.1E-02		52 Fraser Valley	Map/Prev Work
5	Alluvial		283.46	1.0E-01		WPR- Municipal	Numerical
6	Alluvial	12000	34.88	1.2E-02		46 Fraser Valley	Map/Prev Work
7	U. Troublesome	5K-11K				Fraser Valley	Ref Previous Work
8	U. Troublesome	5000	2.23	7.9E-04	300	Fraser Valley	Pump Test
9	U. Troublesome	5000	12.15	4.3E-03		55 Fraser Valley	Map/Prev Work
10	U. Troublesome	1762	0.85	3.0E-04	277	CCR - Domestic	Slug Test
11	U. Troublesome (H dir)		0.28	1.0E-04		Fraser Valley Model	Numerical
12	U. Troublesome	5000	2.20	7.8E-04		304 Fairways - Domestic	Map/Prev Work
13	U. Troublesome	5000	1.77	6.2E-04		378 Fraser Valley	Map/Prev Work
18	U. Troublesome (V dir)		0.14	5.0E-05		Fraser Valley Model	Numerical
24	L. Troublesome	11000	8.65	3.1E-03		170 Fairways - Domestic	Map/Prev Work
26	U & L Troublesome	11000	6.00	2.1E-03		246 Fairways - Domestic	Back-Calculated
30	U & L Troublesome	7152	2.02	7.1E-04		474 Fairways - Domestic	Map/Prev Work

Parameters noted in **"bold red"** have been derived from those parameters provided for the Alluvial and Upper and Lower Troublesome Aquifers

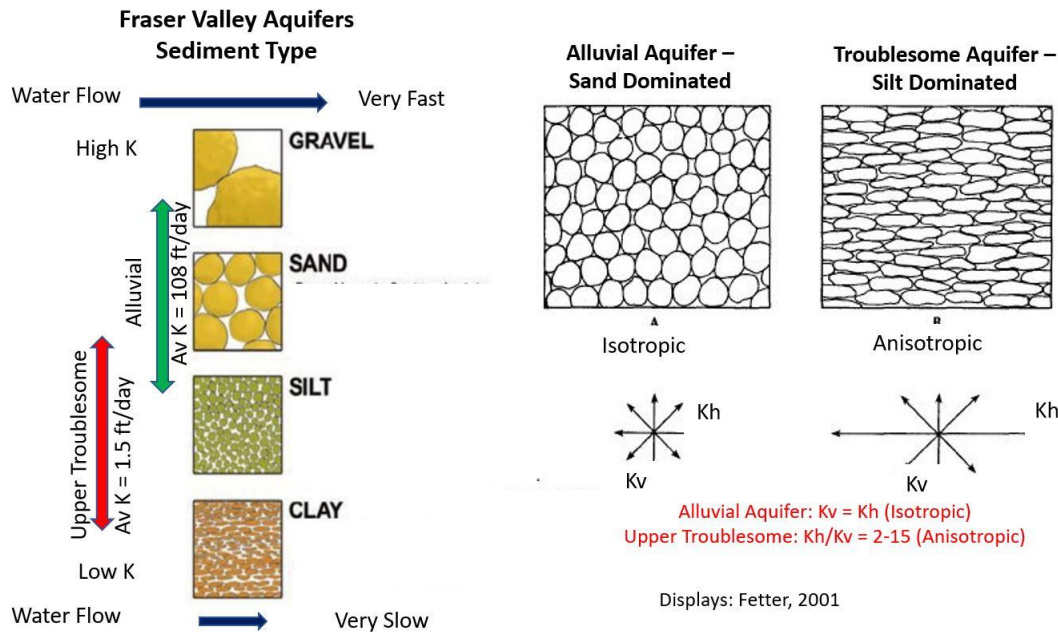


Figure 3-8. Summary displays of type of sediment, relative water flow velocity and average and relative range of hydraulic conductivity (K) (Figure 3-7). The Alluvial Aquifer is mainly composed of sand and gravel with large, interconnected pore-space and thus high conductivity with high velocity water flow. The Upper Troublesome is silt dominated with generally horizontally deposited flat grain sized sediment. These attributes are associated with low conductivity and very slow water flow velocity. In addition, the vertical velocity flow is even slower than the horizontal component, thus moderately anisotropic.

Since only two closely spaced wells extend into the Lower Troublesome Aquifer, very little is known about the sediment make-up and associated hydraulic properties of this interval. Using the sand to silt ratio (N/G) assumptions previously discussed for estimating accessible in-place water volumes, the Lower Troublesome contains substantially greater amounts of sand and therefore may have hydraulic properties similar to the Alluvial Aquifer. With no obvious confining layer evident in drill logs, it is assumed that the Lower Troublesome is hydraulically connected to the Upper Troublesome and is, therefore, unconfined. If tests are conducted in existing or future wells, more reliable estimates of the Lower Troublesome aquifer characteristics can be made to determine its potential value to the communities.

3.4 - Water Consumption

Locations of all existing domestic, commercial, municipal and irrigation (augmentation) wells within the Greater Pole Creek Basin are shown in **Fig 3-9**. Water rights, legal decrees, and associated drilling permits issued within each community dictate the maximum pumping rate and maximum amount of water each well can produce each year. Most domestic wells are allowed 0.25 acre-ft/year (81,431 gal/year) with no outside irrigation, whereas some communities in the northwest Fraser Valley, including the Fairways at Pole Creek and Pole Creek Meadows, are decreed a maximum of approximately 0.35 acre-ft/year (114,003 gal/year) with the option to irrigate a small outside area (approx. 1000 ft²). Most communities within the study area have extensive water augmentation plans to allow for these larger produced volumes. A summary of decreed water use, maximum number of wells, and specified aquifer zones (if any) is provided in **Appendix-Table A3-1a**, **Table-A3-1b** and a map depicting residential developments with augmentation plans is shown on **Appendix-Fig A3-1**. Several high-volume wells are decreed for irrigation and/or augmentation purposes with a current maximum volume of approximately 80-95 acre-ft/year but will only operate when needed. Seven golf course irrigation wells are decreed to pump 50 gal/min (no maximum yearly volume specified with no water production to date). One municipal well serves Pole Creek Valley Community with a maximum allowed production of 123 acre-ft/year. As of 2022, the total well counts of all well groupings equal 431 with a maximum allowable water production of 425 acre-ft/year (**Table 3-3**).

Many of the homes in the study area are second homes and occupied only part-time. In addition, many homeowners own several adjacent lots designated for possible wells that will never be drilled. Therefore, current use is smaller than the maximum allowable consumption volumes or future projections. Most homes with wells are equipped with water meters and homeowners who are associated with HOAs having augmentation agreements are required to report yearly usage to the Division of Water Resources. As of 2024, the meter readings are to be submitted monthly. Detailed daily water usage from water meters would be optimum to monitor domestic water use and help mitigate water waste due to leaks. Homeowners would be required to upgrade to more versatile water meter systems with integrated cellular or Wi-Fi communication technology. The nearby town of Fraser has implemented the 2023 Water Efficiency Plan to include installation of these types of water monitoring meters.

Many of the domestic homes within the study area are second homes and are used only for a portion of the year and the residents are retired or near retirement. For this study, we assume a current usage of 70 percent of maximum consumption and represents more realistic usage due primarily to non-occupancy, and smaller numbers of household members. This subjective assumption includes substantial uncertainty and could range between 50-80 percent. Based on these assumptions, a more realistic current consumption within the Upper Pole Creek Basin is 231 acre-ft/year, with a range of 165-264 acre-ft/year.

The Fraser Valley has seen substantial growth over the past 30 years (**Fig 3-10**). Future projected water usage from the Upper Troublesome Aquifer is based on projected population growth in the nearby town of Fraser and maximum build out of current communities. A projected annual growth of 3.2 percent

(**Fig 3-10**) does not include part-time residents or non-Fraser residents in the valley. Therefore, for future projections, this study assumes a conservative annual growth rate of 3.5% that could easily reach 5-6.5%. The growth rate suggests that the current and planned communities in the Pole Creek Basin depicted on **Fig 3-9** will reach full build-out by 2035 with a total of 735 wells and maximum consumption of 521 acre-ft/year. More realistic future consumption, based on assumed 70 percent of maximum, would be 365 acre-ft/year.

The YMCA of the Rockies is a commercial establishment located in the westernmost portion of the Greater Pole Creek Basin (**Fig 3-9**). This facility relies on an integrated water supply based on an augmentation plan covered by many legacy decrees that are associated with other down-valley developments (**Appendix-Table A3-1b**). The main source for potable water, irrigation and recreational purposes is from diverted surface water (not pumped from Troublesome Aquifer). A maximum water volume of approximately 104 ac-ft/year is diverted from Pole Creek (**Fig 3-9**) and is eventually returned to Pole Creek Valley approximately 0.4 miles east of the diversion point(s) via commercial sanitation facilities. Therefore, the Troublesome Aquifer is not readily affected by this water consumption.

Greater Pole Creek Basin - Troublesome Aquifer Sector Consumptive Usage - Water Producing Wells -2022

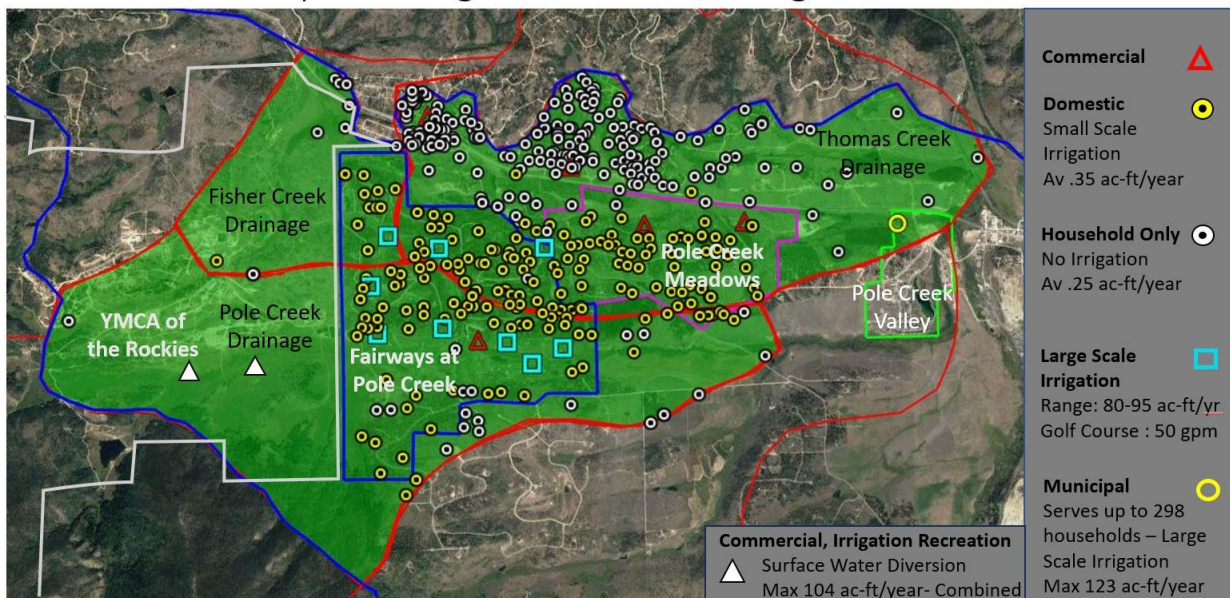


Figure 3-9. Map of all well locations with maximum water consumption type as of 2022 (Colorado Division of Water Resources, 2022) within the Greater Pole Creek Basin. Watershed sub-basins are outlined in red. Types of consumption wells include domestic wells with outside irrigation, domestic household use only, irrigation wells and one municipal well. Maximum water consumption limits and number of wells set by legal decrees.

Table 3-3. Table includes well counts of consumption type with current and maximum numbers of wells and associated water volumes for the year 2022 and projections for year 2035.

Greater Pole Creek Basin - Troublesome Aquifer Sector Consumptive Usage – 2022 Water Producing Wells -2035 Projected Wells

Greater Pole Creek Type of Use	2022 Status		2035 Projected 13 Year	
	Number Wells	Max Allowed Production Acre-Feet	Number Wells	Max Allowed Production Acre-Feet
Commercial	5	2.9	10	5.9
Domestic /Irrigation	187	66.1	366	129.5
Household Only	230	57.5	350	87.5
Irrigation/large scale	8	175.5	8	175.5
Municipal	1	123.0	1	123.0
Total	431	425.1	735	521.3

- 2022 status well count based on permits and well construction records
- 2035 maximum well count based on issued water decrees for residential developments
- Maximum production limits based on water decrees

Greater Pole Creek Basin – Population & Water Consumption Trend

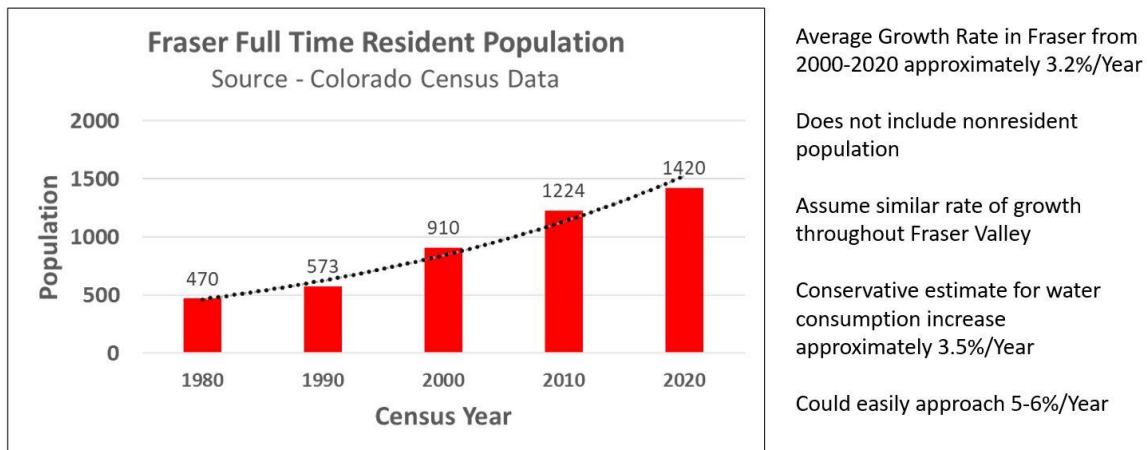


Figure 3-10. Historical population growth of full-time residents within the town of Fraser (Colorado Census Data, 2020).

3.5 – Surface-Water Volume Estimates

Discharge from Pole Creek, Thomas Creek, Skunk Creek and Crooked Creek converge to discharge at the confluence with the Fraser River near Tabernash (**Fig 3-5a**). All these streams have substantial discharge during spring runoff and early summer but become ephemeral in late fall and during winter months. There are no stream gages on any of these four streams, therefore a definitive combined annual discharge is not available.

An indirect streamflow discharge method implements statistical regressions based on analog watersheds in western Colorado (Kircher, 1985). The 1997/1998 BBA report incorporated this type of estimation for Pole Creek and documented a flow volume of 6,518 ac-ft/yr. This streamflow volume is approximately 38 percent of the total estimated volume of water from precipitation within the watershed. This estimation for Pole Creek is very close to the 35 percent streamflow for the entire Fraser Valley documented by Apodaca and Bails (1999). This study used the St Louis Creek watershed, located in the southwestern portion of Fraser Valley, as a nearby analogue and (**Fig 3-5a**). The St. Louis Creek tributary to Fraser River has had continuous streamflow measurements since 1934 (USGS gage station 09026500 / SL-1, **Fig 3-5a**). Average annual streamflow was approximately 17,800 ac-ft/year from 2014-2022. The calibrated average annual precipitation within the Pole Creek watershed of 24,320 acres is 21.5 in/year, and results in an average volume of 43,573 ac-ft/year. The ratio of streamflow to available watershed volume is approximately 41 percent. This is nearly the same as the 43 percent value derived from the same gage station for the years 1934-1997 (Apodaca and Bails, 1999, p 30).

This study uses the 41 percent ratio of streamflow to total watershed water volume as the basis for the Greater Pole Creek Basin 2022 streamflow estimation and future projections (**Fig 3-11, 3-12a-c, 3-14a, 3-14b**). The reduction in precipitation to an average of approximately 13 in/year (**Section 3.1**) produces an estimated streamflow of 4,600 ac-ft/year for 2022.

3.6 – Water-Volume Accounting and Future Projections

This study integrates many of the hydrological components presented above to determine a water budget for the Greater Pole Creek Basin. The basic water budget equation for a small watershed is as follows (Healy and others, 2007):

$P + Q_{in} = ET + \Delta S + Q_{out}$ where P is precipitation,

Q_{in} is water flow into the watershed,

ET is evapotranspiration (the sum of evaporation from soils, surface-water bodies, and plants),

ΔS is change in water storage, and

Q_{out} is water flow out of the watershed.

Assuming no change in storage (Section 2.3), water input to the basin must equal water leaving the basin. Most of the water entering the Greater Pole Creek basin is through precipitation distributed across each watershed plus a very small amount of water recycled through independent septic disposal systems (ISDS) returns.

The ways for water to leave the basin are more numerous and include surface water runoff through streams and rivers, evapotranspiration, and domestic home consumption. Water diversions and extensive agricultural irrigation do not occur in this mountain-valley basin but are relevant in other nearby watersheds in the Fraser Valley. Considerations of groundwater diversions may occur in the future, and their impact should be carefully studied.

Extraction of ground water, whether for domestic or agricultural use, is balanced by a reduction in groundwater storage, a reduction in natural discharge, or an increase in recharge. For any aquifer, all of these phenomena can occur simultaneously, but change in storage (indicated by changing groundwater levels) is usually more easily determined than changes in discharge or recharge (Healy and others, 2007). Most groundwater removed from the subsurface for domestic use eventually ends up returning to the saturated zone through septic leach fields or is discharged to surface-water bodies from wastewater-treatment plants.

The relative magnitudes of these water-budget components are illustrated on **Fig 3-11** and **Fig 3-12a-c**. Water budgets are determined for three different time periods; circa 1997, that incorporate the data from the 1997/1998 BBA Hydrology Report, the current study using 2022 data, and 2022 data projected to 2035. **Fig 3-11** illustrates the volumes associated with each time period with the largest reduction of available water due to change in precipitation. The 2035 projection assumes the drought trend continues and consumption increases with the population increase. The relative percentages of available water leaving the basin for these three time periods are shown on **Fig 3-12a-c**.

Uncertainty associated with each of the water-budget components is difficult to determine. Water lost due to ET likely has the greatest uncertainty. Therefore, this variable is derived as the residual of the water-budget equation. From the years 1997 to 2022, ET has decreased by 40 percent in water volume (**Fig 3-11**) and the largest factor attributed to this reduction is due to the reduction in precipitation. In addition, ET as a percentage of total water leaving the basin has decreased over time, from 46.5 percent to 42.2 percent between 1997 and 2022 (**Fig 3-12a-c**). The resulting percentage reduction may provide some possible insight into the surface conditions that influence the ET component. ET reduction correlates with a reduction in tree cover due to several factors, including a widespread beetle-kill event during 2008 through 2015, residential developments, and creations of firebreaks. Comparison of Landsat images taken in 1994 and 2019 (**Fig 3-13a, 3-13b**) clearly shows the result of these influences. Additional tree removal for the Sheep Mountain firebreak, located on the western portion of the Pole Creek Watershed, has also been conducted in 2022.

Water leaving the basin as streamflow has increased by 2.5 percent from 1997 to 2022 (**Fig 3-12a-c**). This change in surface water flow occurred when vegetative cover in the watershed decreased, and may be related to reduced transpiration, which allowed more runoff to the stream.

All three water budgets (1997, 2022 and projection to 2035) have consistent percent contributions of water-budget components among years. Only the overall quantity of water has changed. In addition, the aquifer water storage (ΔS) is assumed to not change over the decades spanned by these three water budgets.

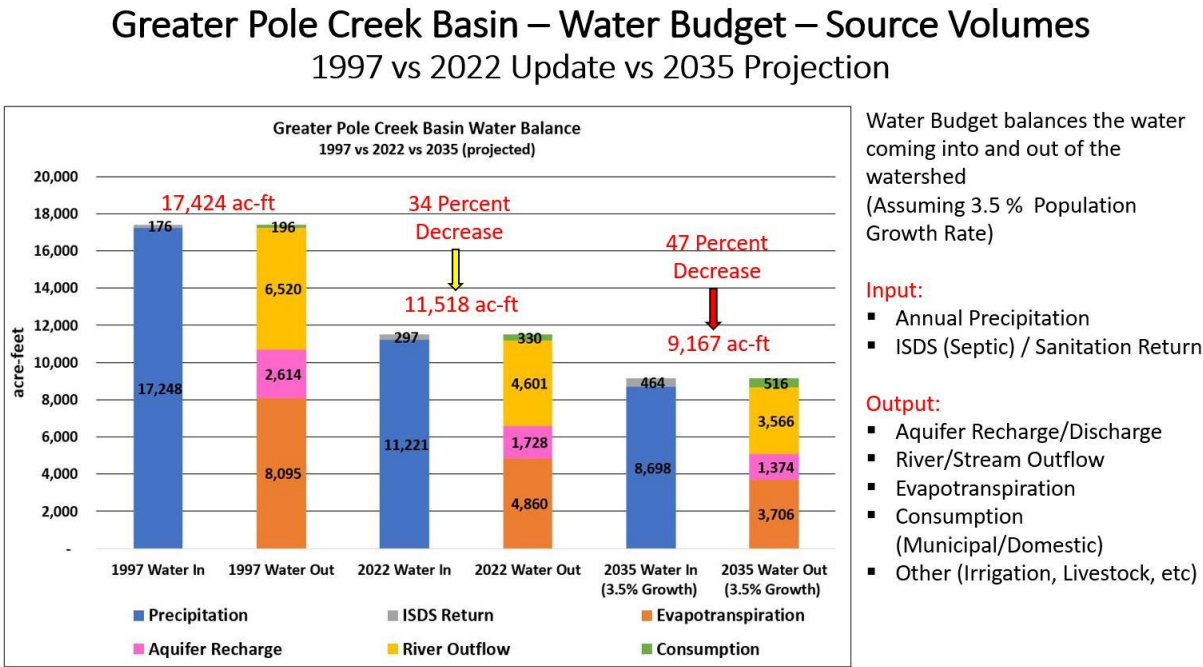
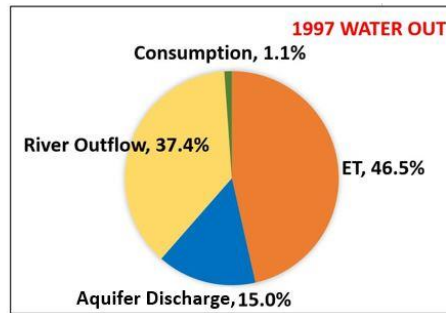
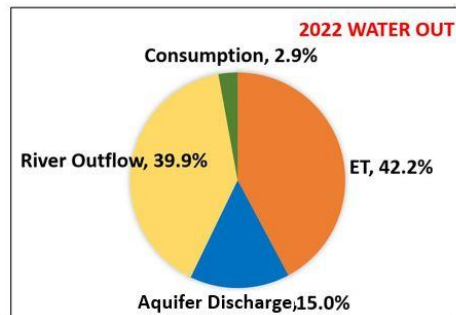


Figure 3-11. Water budget quantities within the Greater Pole Creek Basin during 1997, 2022, and projected for 2035. Total Input and output water volumes are presented separately. Reduced water volumes with time are due to measured and projected reduced precipitation.



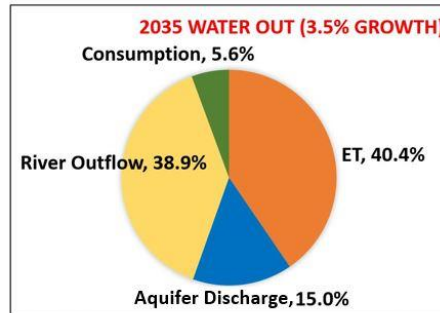
12a

1997/1998 BBA Fairways Report					
Wtrsd acres	precip -in	Aq Rech/Disch	Runoff Coef	Growth Rate	ISDS Eff
9,856	21.0	15.0%	0.38	3.5%	90%
1997 Water In	Type In	1997 Water Out	Type Out		
Ac-Ft	Percent	Ac-Ft	Percent		
17,248	99.0%	8,095 2,614 6,520 196	46.5% 15.0% 37.4% 1.1%	Precipitation	
176	1.0%			ISDS Return	
				Evapotranspiration	
				Aquifer Discharge	
				River Outflow	
				Consumption	
17,424	100%	Total	17,424	100.0%	Total



12b

2022 Estimated Water Balance - Input Parameters & Assumptions					
Wtrsd acres	precip -in	Aq Rech/Disch	Runoff Coef	Growth Rate	ISDS Eff
10,438	12.9	15.0%	0.41	3.5%	90%
2022 Water In	Type In	2022 Water Out	Type Out		
Ac-Ft	Percent	Ac-Ft	Percent		
11,221	97.4%	4,860 1,728 4,601 330	42.2% 15.0% 39.9% 2.9%	Precipitation	
297	2.6%			ISDS Return	
				Evapotranspiration	
				Aquifer Discharge	
				River Outflow	
				Consumption	
11,518	100%	Total	11,518	100.0%	Total



12c

2035 Estimated Water Balance - Input Parameters & Assumptions					
Wtrsd acres	precip -in	Aq Rech/Disch	Runoff Coef	Growth Rate	ISDS Eff
10,438	10.0	15.0%	0.41	3.5%	90%
2035 Water In (3.5% Growth)		Type In	2035 Water Out (3.5% Growth)		Type Out
Ac-Ft	Percent	2035	Ac-Ft	Percent	2035
8,698	94.9%	Precipitation			
464	5.1%	ISDS Return			
			3,706	40.4%	Evapotranspiration
			1,374	15.0%	Aquifer Discharge
			3,566	38.9%	River Outflow
			516	5.6%	Consumption
9,163	100%	Total	9,163	100.0%	Total

Figure 3-12a, 3-12b, 3-12c. Volumes and relative proportions of water-budget output terms for 1997 (**12a**), 2022 (**12b**), and projected for 2035 (**12c**). The analyses assume a decrease in precipitation, 15 percent aquifer recharge rate for all periods, a 0.41 runoff coefficient, 90 percent ISDS return and a 3.5 percent population growth.

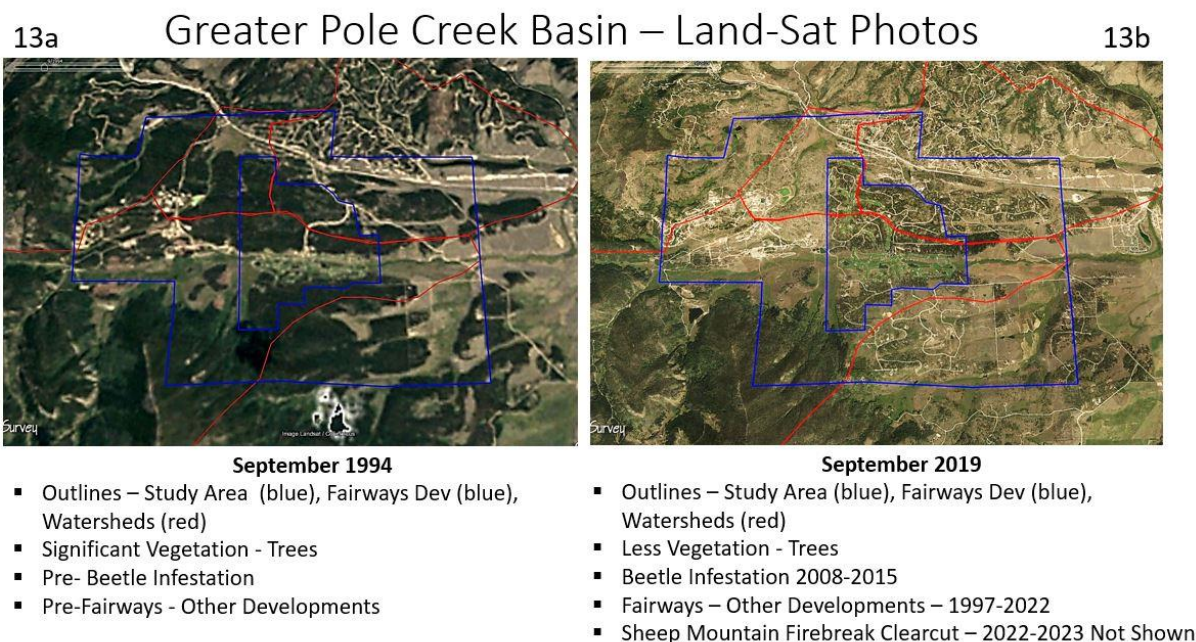


Figure 3-13a, 3-13b. Landsat imagery for the Greater Pole Creek Basin was taken in 1994 (13a) and 2019 (13b). The imagery demonstrates a reduction in forest cover between 1994 and 2019.

3.7 - Upper Troublesome Aquifer Viability – Supply versus Demand Projections

Currently there are no long-term water-table monitoring wells within the Greater Pole Creek Basin. Therefore, direct continuous water-table measurements are not available to infer changes in the aquifer storage (ΔS).

This study has attempted to use projections of water-budget components to determine the sustainability of the Upper Troublesome Aquifer in response to continued reductions in precipitation and several estimates of increased groundwater pumping due to projected increases in residential development. Aquifer recharge analyses are represented by a most likely and reduced-aquifer recharge scenarios. These scenarios are illustrated in **Figures 3-14a & 3-14b** respectively. The analysis assumes the relative percentage of stream outflow and evapotranspiration remains constant and therefore are not included in the volume estimates that affect aquifer storage. The independent variables are precipitation, aquifer hydraulic conductivity and the volume of groundwater withdrawal and subsequent return through ISDS systems. The analyses include data from the historical year 1997 through year 2022 and projected to year 2050. Two sets of curves are illustrated, one (supply curves) based on reduced precipitation and the other (demand curves) based on increasing net consumption. The demand curves are most influenced by the increase in water consumption due to population

growth. Both curve sets include three projected scenarios associated with population growth of 3.5, 5.0 and 6.5 percent after 2022.

For the most likely scenario (**Fig 3-14a**), aquifer recharge is the sum of 15 percent of precipitation and 90 percent of domestic septic-system (ISDS) returns, as discussed previously. The downward trend in recharge is due to reduction in precipitation from 1997 to 2022, a trend that is projected to continue until 2035 (**Fig 3-2**), at which point the area will receive only 10 inches of annual precipitation and levels the same through year 2050. The three curves post 2022 represent increases in aquifer recharge associated with increased ISDS water return for three population growth estimates (3.5%, 5%, 6.5%) and assuming an aquifer-return rate of 90% of consumption.

The Net consumption curve (**Fig 3-14a**) represents aquifer withdrawals due to groundwater pumping. The curve trends upward at a constant rate until 2022 based on a recorded average annual population growth of 3.5% from 1997-2022 and an assumed groundwater pumping rate of 70% of established maximum consumption. Projected groundwater pumping beyond 2022 is based on three population growth estimates (3.5%, 5%, 6.5%), all with pumping rates at 70% of established maximum consumption.

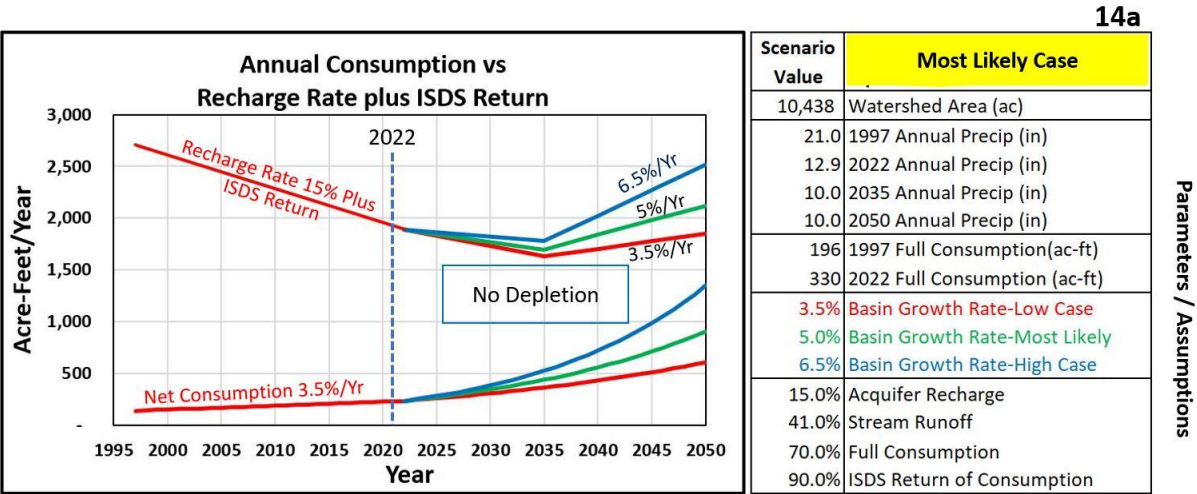
For the most likely scenario, the Recharge/ISDS return (supply) curve is always in excess of the Net consumption (demand) curve. Thus, there is always a surplus of accessible water in the Upper Troublesome aquifer with no concern for depleting the aquifer.

A second reduced-recharge scenario was derived to test several factors that would contribute to lower Upper Troublesome Aquifer recharge projection estimates (**Fig 3-14b**). This Recharge/ISDS return versus Net consumption graph incorporates reasonable assumptions that have a smaller probability of occurrence:

- (1) A drought continuing until 2050, at which annual precipitation would be reduced to 8 inches and would constitute severe environmental conditions impacting cultural and development activities.
- (2) Smaller aquifer recharges of only 7.5 percent of precipitation is a reasonable possibility since there is a high degree of uncertainty of the average hydraulic conductivity (K) of the Upper Troublesome Aquifer. Recharge percentage is directly proportional to aquifer K according to Darcy Law (Heath, 1983). The most likely case scenario considers a K of 2.2 ft/day based on reported well drawdown pumping tests (Bauch and Bails, 2004) and equates to 15 percent aquifer recharge rate. K estimates from well slug tests range as low as 0.9 ft/day (Aigler and Ge, 2012) and would equate to a recharge percentage of 6.6 percent.
- (3) A larger groundwater pumping rate at 80 percent (as opposed to 70 percent) of established maximum consumption may occur when greater residency rates are realized.
- (4) A smaller ISDS water return to aquifer of only 60 percent as opposed to 90 percent may be attributed to more efficient use of household water, or water infiltrating from the septic systems contributing to stream runoff rather than aquifer recharge.

The combination of these changes resulted in the supply and demand curves intersecting and initiating aquifer depletion starting around 2048 (**Fig. 3-14b**), assuming a 6.5 percent population growth rate. As previously mentioned, this would be a worst-case scenario that is highly unlikely. These estimates suggest that there should be little concern for shortage of Upper Troublesome Aquifer water for the next 25+ years. One caveat to this conclusion is if large volume groundwater diversions are considered in the future. Given the most likely scenario (**Fig. 3-14a**) and the volumetric difference between the supply and demand curves, any water diversions more than 1000 ac-ft/year may initiate aquifer depletion.

Assuming that water supply in the Upper Troublesome Aquifer is likely to be adequate, aquifer-management attention should be directed toward well-flow considerations and water usage adhering to decreed consumption amounts discussed previously and in **Section 4.2**. In addition, water quality within the Upper Troublesome requires testing for anomalous excessive concentrations of naturally occurring metals and major ions as discussed in **Section 5**.



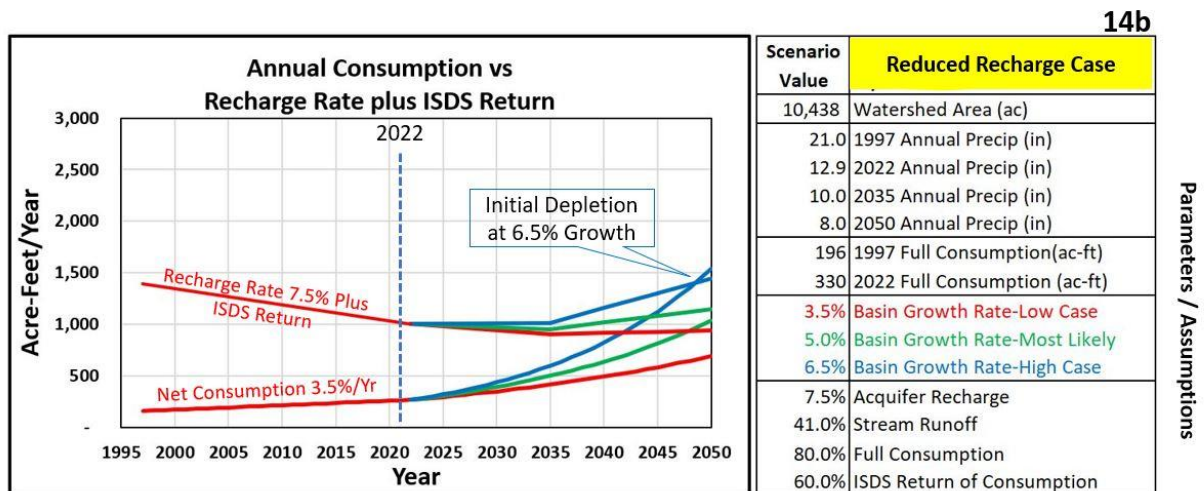


Figure 3-14a, 3-14b. Observed and projected Upper Troublesome Aquifer recharge versus observed and projected water-well extractions for the Greater Pole Creek Basin assuming (14a) aquifer recharge at 15 percent of precipitation or (14b) aquifer recharge at 7.5 percent of precipitation. Net water-consumption projections are based on assumed population growth of 3.5 (red line), 5.0 (green line) or 6.5 (blue line) percent.

4 - Water-Well Construction and Deliverability

4.1 – Water-Well Construction Options and Deliverability

Wells in the Greater Pole Creek Basin have been drilled to target one or more clean sand intervals. Once the water producing sand interval(s) have been located, the well is then completed by installing a casing string, usually 4" (4½" O.D.) PVC pipe, to the desired depth. The casing string includes sections of well screen of the same diameter as the PVC pipe with screens/perforations set at depths corresponding to the sand interval(s). The screen slot size (width of the screen openings) is selected to minimize transport of sediment through the screen and into the well. The annulus (the volume between the well screen or casing and the outer diameter of the drill hole) surrounding screened intervals is filled with permeable sediment with a grain diameter larger than the width of the openings in the screen. Aquifer water then flows through the filter/sand pack surrounding the well screen, through the screen, and up the well casing as it is pumped to the surface. A schematic of a water-well design commonly installed in the Fraser River valley (**Fig 4-1a**) shows two sets of well-bore dimensions. The smaller 6 ⅝" - 6 ¾" diameter hole is typical of most domestic wells in the Fraser Valley. The larger dimensions associated with an 8" diameter hole are relatively new to the Fraser Valley drilling procedure, and the advantages will be discussed subsequently.

Many homeowners experienced minor to considerable silt contamination in their well water and installed water filters to address the problem. A few homeowners experienced total well failures that were discussed in **Section 2.2** and shown in **Fig 2-7**. To date, within the study area, six known wells required replacement (**Table 2-1**) and one had a major work-over, all at considerable expense.

The standard construction of residential wells in the valley has a 6 ⅝"-diameter borehole and 4 ½" O.D. casing, which leaves an annular distance of approximately 1" (**Fig 4-1a**). The wells were drilled according to Colorado state regulations, (2CCR 402-2, Section 10.4.6.2c, 2016, p 35-36). The construction rules specifically state, along with supporting illustrations, that wells drilled into an unconsolidated and unconfined Type II aquifer (**Fig 1-5**), characteristic of the Upper Troublesome, need not have a filter pack, sealant or grout emplaced within the annulus.

Consultation with an experienced local drilling contractor, who replaced several of the wells, provided some insight into the failure of the original wells. The failures were due to excessive silt build-up ("caking") on the screens that would greatly reduce the rate of water flow through the screen and into the house. Attempts to clean the screens mechanically or chemically were not successful, too costly, or undesirable.

The drilling contractor indicated that, when the wells were pumped, water could rapidly flow through the unoccupied annulus to the well screen, entraining and transporting silt to the well screen. Some silt would pass through the well screen, and some would accumulate ("cake") at the outer surface of the screen, thus partially clogging the screen and reducing the water-flow rate into the casing. Where two or more sand intervals are separated by silt intervals, all within the same screened interval, silt

contamination and clogging could worsen. To solve this problem, it was necessary to fill the annulus with sediment that would not allow movement of silt along the annulus to the well screen. For new wells drilled within the Troublesome, the annulus is generally filled with silica sand. For a 6 $\frac{3}{8}$ "-diameter borehole, a 1" annulus is too narrow for effective insertion of sand or other material to occupy the annulus.

Given that several of the originally designed wells required treatment or replacement, a slightly different well design was implemented. A larger, 8" diameter, borehole was drilled, still with insertion of 4 $\frac{1}{2}$ " diameter PVC casing. This nearly doubled the width of the annulus, allowing effective emplacement of selected sediment between the casing and the borehole wall (**Fig 4-1a**). This filter/sand pack, which also has a much larger vertical extent than the well screen(s), allows slower flow of water to the well screen with a much-reduced transport of entrained silt and substantially reduces movement of silt to the screens. If multiple sand zones are intended for water production, the filter/sand pack extends across all the zones including the intervening silt intervals.

Three drilling-completion options are illustrated on **Fig 4-2**. Option 1 ("adequate") depicts the standard completion used for most wells in the study area with an empty well annulus at the screen depth. Option 2 ("better") demonstrates sand-pack emplacement with a single screened interval in the well string. Option 3 ("best") is a silica-sand pack placement when multiple sand zones are intended for water production. For wells drilled and completed in the Upper Troublesome Aquifer, options 2 or 3 are preferable to minimize silt contamination.

Each state makes their own regulations for drilling domestic water wells based on geologic and aquifer conditions. Many states have regulations that specifically indicate the option for emplacement of the "sealant," usually a silica-sand pack, within the annulus for unconsolidated unconfined aquifers. Wyoming's regulations for this type of well completion (Wyoming State Engineer's Office, 2011). describe this as a Type III -Artificial Filter Well (Chapter 3-Section 2b(iii), p 2&3, Appendix C-3). In Colorado, well drilling regulations have been slow to change to accommodate these issues but are currently being reviewed by the state agencies. A 2023-2024 revision is pending.

Well drilling logs, construction information and test reports for most domestic and municipal wells are available through an interactive Colorado Division of Water Resources website at [Map Viewer \(state.co.us\)](https://mapviewer.state.co.us). Each well report contains the drilling-log information with descriptions of sand and/or water producing zones. Borehole size and well-completion details, including casing diameter, screened intervals, and filter/sand pack placements (if done), are provided. As examples, **Fig 4-3a and 4-3b** depict drilling logs and completion reports from two closely spaced wells. The left well has a smaller borehole and no filter/sand pack while the right well has a larger borehole with the sand/pack emplacement.

Fraser Valley - Domestic Well Design and Aquifer Type

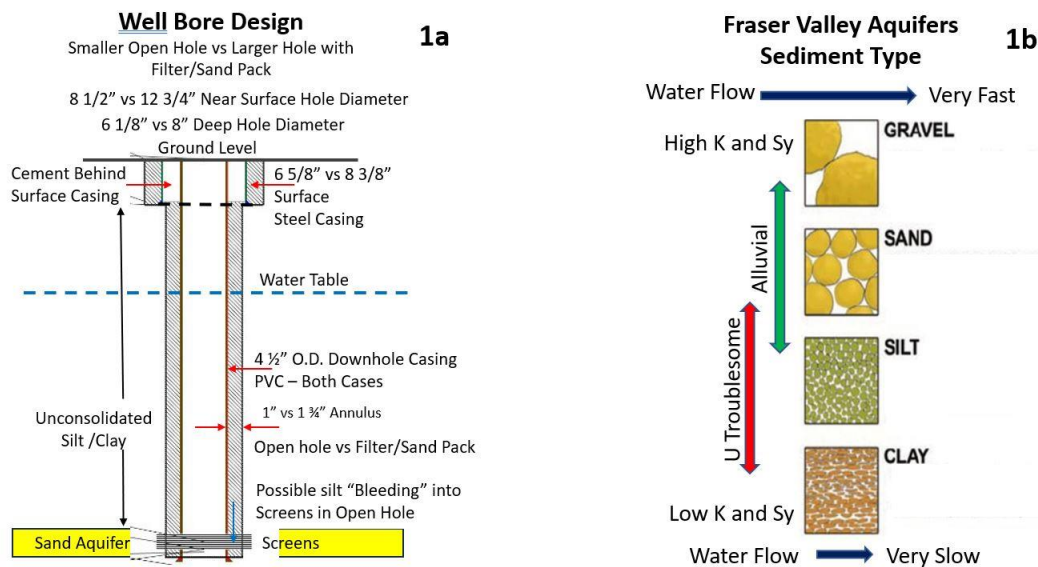


Figure 4-1a & 4-1b. Water well design (1a) with two versions of hole dimensions for well construction and types of sediment composition and relative hydraulic properties (K and S_y) in Fraser Valley aquifers (1b).

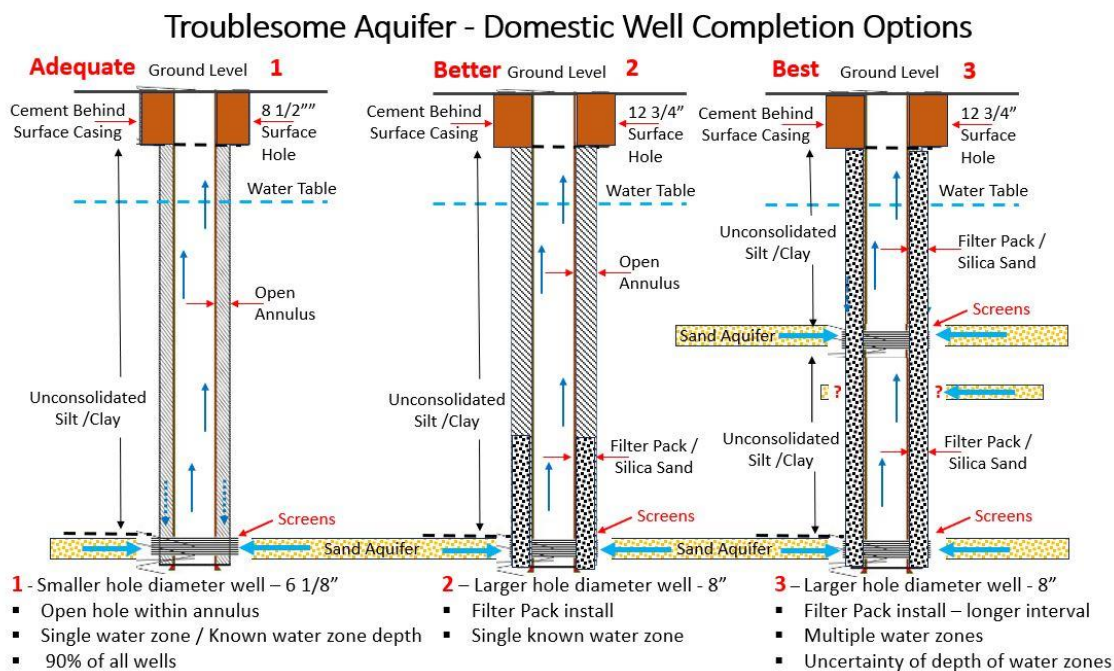


Figure 4-2. Summary display of three well completion techniques based on well bore design and related risk mitigation to sediment intrusion drilled in unconsolidated sediment. Wells completed with smaller well bores and no silica sand packing (1) are adequate for many unconsolidated aquifers but may be problematic under certain circumstances. Wells completed with a larger well bore and silica sand pack emplacement near the producing

water sand (2) minimizes the sediment intrusion risk. When multiple water sand intervals are produced along with uncertainty of depth to those intervals, then wells completed with a full silica sand pack from ground level to total depth (3) is the best option. The sediment intrusion risk is higher within the silt dominated Upper Troublesome and less so within the sand/gravel dominated Alluvial Aquifer (Fig 4-1b).

3a

Small Hole Size Well
—
No Silica Sand Filter Pack

Sediment Type & Interval

Water Sand Interval

Water Table Measurement post Well Const

4. GROUND SURFACE ELEVATION Unknown ft. DRILLING METHOD Air
DATE COMPLETED 12-8-99 TOTAL DEPTH 300 ft. DEPTH COMPLETED 300 ft.

5. GEOLOGIC LOG:
Depth Description of Material (Type, Size, Color, Water Location)
0 2 topsoil
2 17 Clay & gravel
17 103 Clay
103 157 Gravel & clay
157 236 Clay
236 274 Sandstone xx
274 276 Clay & gravel xx
276 300 Sandstone
300 300 Clay

6. HOLE D/IAM. (in.) From (ft) To (ft)
8.5 0 23
6.1/8 23 300

7. PLAIN CASING
OD (in) Kind Wall Size From (ft) To (ft)
6.5/8 Steel .188 +1 2
4.5 P.V.C. .214 12 200

PERF. CASING: Screen Slot Size: .032
4.5 P.V.C. .214 200 300

8. FILTER PACK:
Material
Size
Interval

9. PACKER PLACEMENT:
Type Rubber
Depth 80 ft

10. GROUTING RECORD:
Material Amount Density Interval Placement
cement 188# 15# 8-20 Poured & vibrated

REMARKS:

11. DISINFECTION: Type H. T. H. Amt. Used 5 Oz.

12. WELL TEST DATA: ☐ Check box if Test Data is submitted on Form No. GWS 39 Supplemental Well Test.
TESTING METHOD Air
Static Level 150 ft. Date/Time measured 12-8-99 Production Rate 12 gpm.

3b

Large Hole Size Well
—
With Silica Sand Filter Pack

Sediment Type & Interval

Water Sand Interval

Water Table Measurement post Well Const

7. Ground Surface Elevation: 8650 feet Date Completed: 10/07/2016 Drilling Method: Air Rotary
8. Completed Aquifer Name: Troublesome Total Depth: 400 feet Depth Completed: 400 feet

9. Advance Notification: Was Notification Required Prior to Construction? ☒ Yes ☐ No, Date Notification Given:
10. Aquifer Type: ☐ Type I (One Confining Layer) ☐ Type I (Multiple Confining Layers) ☐ Laramie-Fox Hills
(Check one) ☒ Type II (Not overlain by Type III) ☐ Type II (Overlain by Type III) ☐ Type III (alluvial/colluvial)

11. Geologic Log:
Depth Type Grain Size Color Water Loc.
0-57 Clay/gravels crse brn
57-236 siltstones w/clay med/fine brn/tan
236-238 sandstone fine/hard tan x
238-346 siltstones w/clay fine brn/tan
346-349 sandstone fine/hard tan xx
349-400 siltstones med/fine brn

12. Hole Diameter (in.) From (ft) To (ft)
12.75 0 62
8.0 62 400

13. Plain Casing
OD (in) Kind Wall Size (in) From (ft) To (ft)
8.625 Steel .250 -1 2
4.5 PVC .237 5 340

Perforated Casing
OD (in) Kind Wall Size (in) From (ft) To (ft)
4.5 PVC .237 340 400

14. Filter Pack:
Material Silica Sand
Size 8-12
Interval 400-60

15. Packer Placement:
Type N/A
Depth

16. Grouting Record
Material Amount Density Interval Placement
Spec 48Bgs 15.6 0-62 mix pumped
cement trem

REMARKS:

17. Disinfection: Type DRY HTH Amt. Used 3.5 Cups

18. Well Yield Estimate Data: ☐ Check box if Test Data is submitted on Form Number GWS-39, Well Yield Test Report
Well Yield Estimate Method: AIR LIFT
Static Level: ±100 Estimated Production Rate ±18 gpm.
Date/Time measured: 10/07/2016 Estimate Length (hrs) 2

Figure 4-3a & 4-3b. Example drilling logs and completion example reports from two wells with different drilling and post-drilling construction procedures. The wells are approximately 300 feet apart. Some wells are drilled with

smaller 6 1/8" diameter holes (**3a**) whereas other more recent wells are drilled with larger 8" diameter holes (**3b**). Depth of water sands are identified along with casing and screen depth intervals shown on both well reports. The smaller hole size well (**3a**) has no reported filter pack whereas the larger hole sized well (**3b**) indicates filter pack with the silica sand and emplacement interval.

4.2 – Water-Well Production Considerations and Best Practices

Most residential wells completed in the Upper Troublesome are not sufficiently compromised to require replacement. To mitigate reduced production due to silt-induced clogging, excessive pumping rates should be avoided. Homeowners should adhere to the state regulated maximum annual volume of water consumed and specified on the well permit (**Table 4-1a**). Pumping excessive volumes of water over a short period, due to outside irrigation, accidental massive plumbing failure or other reasons, can mobilize silt that otherwise would not be transported through the screen to the home. Homeowners may consider alternatives to outside spray sprinklers, such as passive drip irrigation, or shutting off the water supply when away, or installing an automatic shut-off to plumbing if an anomalously large pumping rate is detected.

Because the Upper Troublesome Aquifer does not usually provide high yields, many homes require a moderate-volume pressure tank to provide additional water storage. Lower yield wells require larger in-house water storage to maintain acceptable water pressure. Extremely low yield wells require a very large pressure tank, sometimes including an above-ground storage tank or cistern. Well yield and normally installed pressure tank size are summarized on **Table 4-1b**. Several recent options are available to reduce “shocking” the aquifer with continued high rates of pumping, including “smart” storage tanks or cisterns. These tanks hold a considerable volume of water that is replenished by running the pump at slow to moderate rates during times of minimal in-home use. These systems reach higher pressures than conventional tanks, thus allowing higher rates of water supplied to the household. A schematic of this type of system is provided on **Fig 4-4**. These types of water-storage systems are also used for low-production wells installed in fractured crystalline rock where water yield is insufficient to meet typical residential water-use demands.

Table 4-1a, 4-1b. Colorado State regulations on annual maximum volumes of water pumped from domestic wells, including assumed average household water consumption and, in some cases, minimal irrigation (**1a**). Summary of domestic water well yield rates versus in-house water storage (**1b**).

1a State Allocated Maximum Water Use - Well Permits and Water Rights Decreases

State Regulation Use Category	Maximum Water (ac-ft/year)	Maximum Water (gal/year)	Outside Irrigation	Approx Irrigation (gal/year)	Augmentation Plan
Household	0.25	81,431	None	None	None
Domestic - Residential Developments	0.35	114,003	1000 sq ft	32,572	Yes

Assumptions:

3.5 persons/home

80 gallons/person/day = 280 gallons/day = 102,200 gallons/year

80% occupancy time = 81,760 gallons/year (approximately 0.25 ac-ft/year)

1b Well Yield and Water Storage

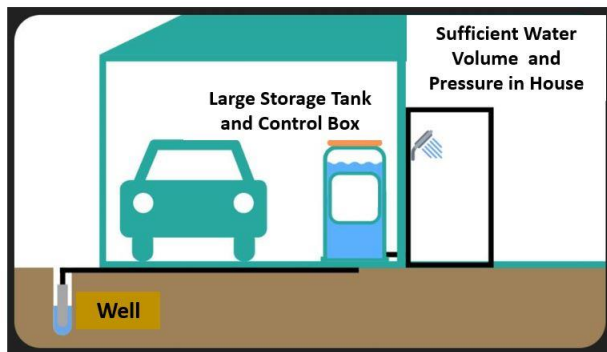
Domestic Water Well Yield (gal/min)	>10	5	2-3
Advised Water Storage (gallons)	None	20-40	200+

Assumptions:

Most home mortgage companies require minimum >5 gal/min yield

Combined well yield and water storage necessary for running two average fixtures/appliances at same time

Reduce the High Rate of Well Pumping Possible Water Storage Alternatives



- Available from Various Vendors
- Compatible with Existing Water Well Equipment
- Cost Effective Alternative
- **Water Production –**
Slowly Pump Water During Times of Minimal Use
- Water Storage Tank – In Excess of 200 Gallons (adding additional tanks as needed is possible)
- Smart Computerized System –
Daily and Seasonal Optimization for Water Table Variations
- Booster Pump to Maintain Constant Pressure in House –
Up to 60 psi from Storage Tank(s)
- Protects well from “Over Pumping”
- Environmentally Friendly

Figure 4-4. Schematic of water-harvesting equipment that provides an alternative to low water pressure and protects the well-aquifer interface from high pumping stress.

5 - Troublesome Aquifer Water Quality

5.1 – Water-Quality Purpose and Scope

Within the Greater Pole Creek Basin, the Troublesome Aquifer serves as the main source of groundwater for domestic wells (**Fig 3-9**). Contamination of this groundwater supply would have serious consequences. Most previous groundwater assessments concentrated on the shallow Alluvial Aquifer within the central portion of the valley, east and south of the study area (**Fig 3-5b**). There have not been any publications of groundwater geochemical assessments of the deeper Troublesome Aquifer.

This report presents the published Alluvial Aquifer groundwater-quality assessments and the relatively limited and available Troublesome groundwater geochemical information. There are several factors that relate to the Troublesome groundwater quality, inclusive the rock type the water initially flows prior to recharging the aquifer, the aquifer rock type and the resident time within the aquifer. The scope of this study extends to the deeper portions of the Troublesome Aquifer thanks to data from the “key” TMWS #2 well, located just east of the study area (**Fig 1-1b, Fig 5-1**). Data from this and other deeper wells allows geochemical variations of groundwater to be related to aquifer depth. In addition, several additional data points for the deeper Troublesome wells are provided (locations confidential).

Another intent is to inform area homeowners of water-quality variations within the Troublesome Aquifer and advocate for more comprehensive water-quality surveys and analyses going forward. These are needed to fully understand the nature of the geochemical makeup of the deeper Troublesome Aquifer that an increasing number of domestic homeowners rely on within the Greater Pole Creek Basin.

5.2 – Factors that Influence Groundwater Geochemistry

Nearly all groundwater in the Greater Pole Creek Basin originates as snowmelt (Bauch, 2000). Water runoff from the higher elevation within the watershed (**Fig 1-4a-b, Fig 3-4a**) and basin snowmelt infiltrates through fractured crystalline rock and soil into the underlying aquifers. A Potentiometric Map (**Fig 5-1**) illustrates the horizontal hydraulic gradient and direction of flow at and near the water table of the Troublesome and/or the Alluvial Aquifers. The water quality within these aquifers is subject to the geologic materials within the aquifers and the groundwater residence time. Solutes are leached from sediments as water flows through the sediments above and within the aquifer. As water slowly flows through the aquifer, solutes continue to accumulate in groundwater along flow paths from recharge to discharge areas, its chemistry being additionally altered by the effects of a variety of geochemical processes.

Water residence time is generally much shorter for flow through sand than silt. If sandy extents within more massive silt sections are discontinuous, or if the deposit is faulted, then groundwater within each

sand interval may be partially isolated with longer residence times and have different oxidation states. These spatial and temporal considerations may result in a broad range of chemical constituents and concentrations contained in the groundwater over short distances. The water chemistry and chemical concentration commonly is directly proportional to the residence time of the water within the aquifer. **Fig 5-2** depicts a generalized diagram of the hypothetical flow within the unconfined Troublesome Aquifer. As discussed in **Section 3.3**, the silt-dominated Troublesome Aquifer has hydraulic properties that indicate 50-100 times slower flow velocity than that of the sand/gravel Alluvial Aquifer. Hydraulic gradient is the other key flow-velocity factor that is related to the geometry of the basin (width, length, and depth) as well as the overall gradient across the basin from recharge to discharge areas. Any barriers present, such as impermeable shale layers, complex geometry of sand bodies, or faults (**Fig 2-5a, 2-5b, 2-7a-c**) can further impede flow through the aquifer.

Previous studies have measured the age of the water, from recharge to discharge areas, within the Alluvial Aquifer (Apodaca, 2000). Using measurements of chlorofluorocarbons (CFCs -- manmade compounds incorporated into refrigerants and other uses) present in the water; the water age has been estimated at 18-38 years (**Fig 5-3**).

Water moving through the Troublesome Aquifer, particularly the deeper portions, is considerably older. Given the generally smaller hydraulic conductivity, longer flow-path length, and other flow-impeding factors, the age of water could be hundreds to thousands of years (**Fig 5-2**). The average hydraulic conductivity of the Troublesome Aquifer is approximately 74 times smaller than that of the Alluvial Aquifer (**Section 3.3, Fig 3-7, 3-8**). Assuming a similar flow path length within the Troublesome Aquifer as considered by Apodaca (2000) for the alluvial aquifer, water in the Troublesome water could be 1,300-2,800 years old.

These longer groundwater-residence times affect the geochemical makeup of these waters. No published reports of groundwater age are available for the Troublesome Aquifer, but future studies should include water-age analyses, possibly using ³⁹Argon and ¹⁴Carbon isotopes (**Fig 5-3, Kralik, 2015**) given that the water likely is too old for age-dating using CFC analysis. Water-age estimates could be obtained from various well samples over the study area, specifically at different distances from the basin-margin recharge areas. Other age-dating estimates may implement numeric simulations with geologic models replicating the aquifer properties and basin geometries.

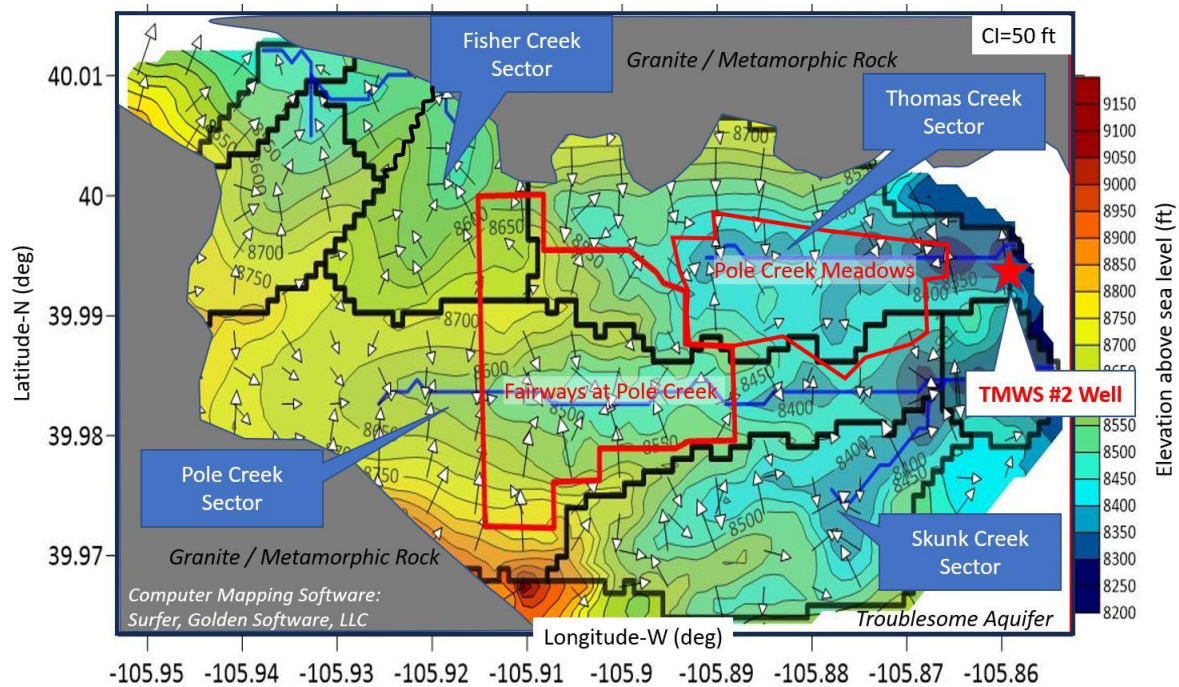
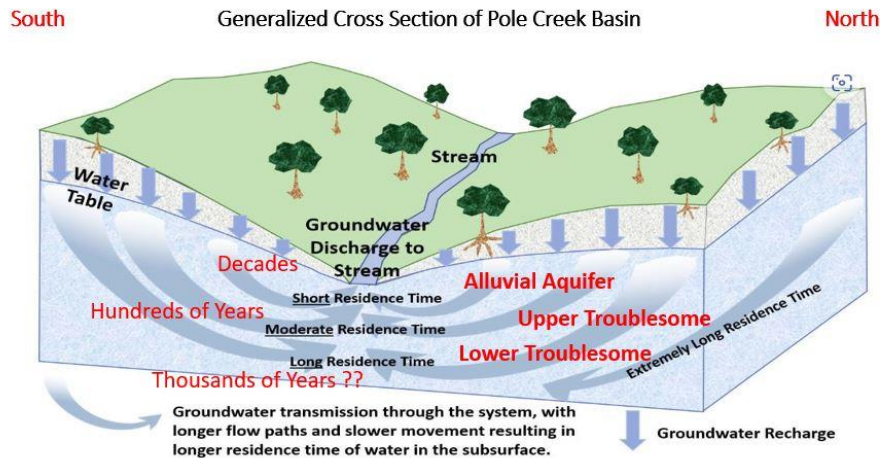


Figure 5-1. Potentiometric map with watershed sub-basins (“sectors”) within the Greater Pole Creek Basin. Contours lines indicate the water-table elevations in feet. The general flow direction is from west to east, where groundwater discharges to the Fraser River. The key Tabernash Meadows Water and Sanitation municipal well (TMWS #2), indicated by a red star has excellent geophysical logs for the aquifer geochemical assessments.

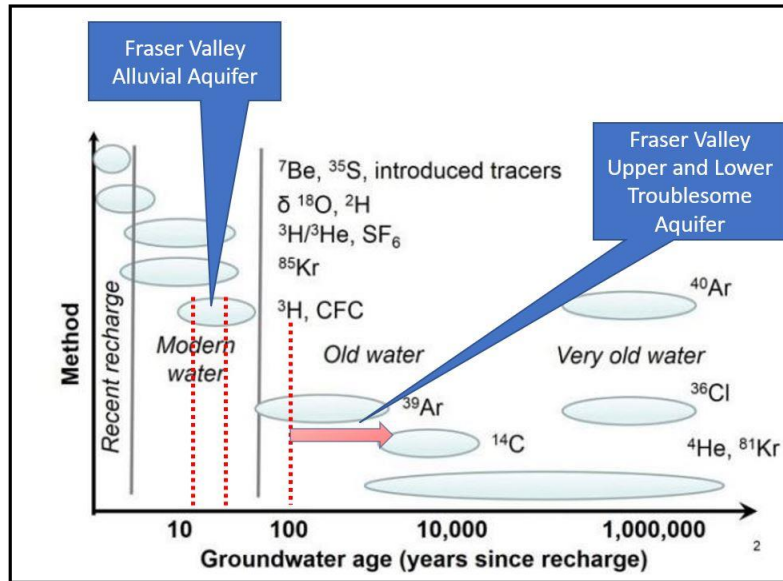
Troublesome Aquifer Water Residency - Age



Modified from Porter et al., gwproject.org, 2020

Figure 5-2. General groundwater flow diagram for an unconfined aquifer demonstrates the relative water age as a function of depth (Porter, and others, 2020).

Methods for Measuring Mean Residence Times of Groundwater



Modified from: Martin Kralik / Procedia Earth and Planetary Science 13, 2015

Figure 5-3. Summary of methods to determine groundwater residence time (modified from Kralik, 2015). ^7Be = Beryllium-7, ^{35}S = Sulphur-35, $\delta^{18}\text{O}$ = a measure of the ratio of stable-isotope Oxygen-18 to Oxygen-16, ^2H is the stable deuterium isotope of hydrogen, $^3\text{H}/^3\text{He}$ is the ratio of Hydrogen-3 (“tritium”) to Helium-3, SF_6 is Sulfur hexafluoride, ^{85}Kr is Krypton-85, ^{40}Ar is Argon-40, CFC is Chlorofluorocarbon, ^{14}C is Carbon-14, ^4He is Helium-4, and ^{81}Kr is Krypton-81. Groundwater in shallow and sand prone aquifers (less than 100 years old) can be aged with methods that use man-made compounds. Older water requires measurements of Argon or Carbon isotopes.

5.3 – Previous Groundwater Studies, Well Database and Annual Testing

Past water-quality studies in the Greater Pole Creek Basin emphasized surface water and shallow groundwater that may have been impacted by home development and golf course operations. The most frequently analyzed water-quality parameters include ammonia, chloride, dissolved oxygen, nitrate/nitrite, orthophosphate, phosphorous, specific conductance, and temperature. Most previously reported groundwater analyses were of groundwater sampled from shallow Alluvial Aquifer wells with only two analyses from shallow Troublesome wells.

One of the first comprehensive water-quality investigations in the Fraser Valley was conducted by the USGS in 1997 in cooperation with Grand County and Colorado Department of Health and Environment (Apodaca and Bails, 1999). The study’s scope provided an assessment of the quantity and quality of

the water resources in relation to land use/land cover. Emphasis was placed on collecting water samples from 72 surface sites and 9 shallow groundwater wells throughout the Fraser River watershed. Only two shallow Alluvial Aquifer wells were in the Greater Pole Creek Basin.

After the initial report, the USGS conducted additional groundwater-quality studies that were based on the collection of groundwater samples between 1998-2001 within Fraser Valley. Data analyses and associated reports were published in cooperation with the Grand County Board of Commissioners in 2000 and 2003. The first report was based on analyses from 20 wells within Fraser Valley during the year 1998 (Apodaca, et. al, 2000). Fifteen of these wells were screened in the shallow granite and/or Alluvial Aquifer whereas only 5 extended to the uppermost Troublesome Aquifer, with an average depth of 106 feet for all wells. A 12-well subset of this group was located at the far eastern portion of this study area, near Tabernash, within the Greater Pole Creek Basin.

The subsequent USGS report published in 2003 implemented detailed statistical water quality analyses of a subset of the 20-well group (Bauch and Bails, 2004). The sampled data was from 11 wells and one surface-water location within the valley. Within the Greater Pole Creek Basin, only 6 wells were included in the study, 3 shallow Alluvial Aquifer wells near Tabernash with an average depth of 39 feet, and 2 Upper Troublesome wells averaging 208 feet in depth. One sampled well, 105-feet deep, was completed in fractured granite. The analyses for both USGS reports included concentrations of dissolved solids, major ions and trace elements, which are relevant to this study for comparison purposes.

Prior to the large-scale home developments, several additional hydrologic studies were conducted in the area. One report, conducted by Bishop-Brogden Associates Water Consultants (BBA, 1997, amended in 1998) for the Fairways at Pole Creek Development was required by Grand County Zoning Department. The BBA report incorporated 33 wells. Except for two YMCA wells, both more than 600 ft deep and decreed for irrigation/augmentation purposes, the average depth of the remaining 31 domestic wells is approximately 139 feet. Most of the shallow wells were completed in the uppermost section of the Troublesome and/or Alluvial Aquifers. For water quality, the BBA report relied on previous analyses from nearby shallow YMCA wells, Pole Creek Golf Club wells, and a few private wells near Tabernash. Analytes included nitrates, fecal coliform, and selenium, with concentrations indicated as “acceptable safe levels” (BBA Hydrology Report, 1997/1998).

Since the USGS reports were published 20 years ago, there has not been any apparent available published report of water analyses from the deeper water sources within the Troublesome Aquifer. From approximately 1998 through 2022 there has been considerable home development in the Greater Pole Creek Basin with associated drilling of deeper private domestic wells. Based on state well records (Colorado Division of Water Resources) and well data included in this report, approximately 217 wells were drilled during that period. Drilling depths range from 175 to 1100 feet with an average depth of 372 feet. Wells deeper than 350 feet, number 120. All these wells were drilled into the Troublesome Aquifer with the deeper wells encountering the lower portion of the aquifer (**Fig 5-11, 5-12**).

Most home development HOAs within the Greater Pole Creek Basin require annual testing of water from the homeowner domestic wells. The tests are for the presence or absence of total coliform and E coli fecal coliform only. These tests help determine if there are any issues related to the individual septic disposal systems (ISDS) or other near-surface contamination sources. No other tests are required, although individual homeowners may conduct more detailed water-quality evaluations without having to report findings to any county or state agencies.

5.4 - Key Deep Troublesome Well

5.4.1 - Review of Water Quality Testing – Initial Well Construction versus Recompletion

The Tabernash Meadows Water and Sanitation well (TMWS #2) was drilled to a total depth of 518 feet and completed in the Troublesome Aquifer in 2005 with a bottom casing depth of 462 feet. Five screened intervals draw water from depths ranging from 170 to 450 feet (**Fig 5-4**). After lengthy pumping, initial water-quality analyses indicated high concentrations of fluoride that averaged 12.3 mg/L with values as high as 16 mg/L. These values were well above the EPA maximum contamination level (MCL) for drinking-water consumption of 4 mg/L (U.S. Environmental Protection Agency, 2009). Many municipal water providers maintain a fluoride concentration of 0.7-1.2 mg/L for optimum dental health, whereas consumption of water with concentrations greater than the MCL for fluoride could have adverse health effects (U.S Department of Human Services, 2015). Water removed from the well also had pH as high as 9.5 and total dissolved solids (TDS) of 398 mg/L, both substantially higher than results from any other sampled wells in the Fraser Valley. Concentrations of these constituents are both in the highest category from a contamination perspective (McMahon et al., 2020).

Due to the high level of fluoride, screened intervals deeper than 300 feet were grouted to remove those intervals from production (“recompletion”) in 2014 (**Fig 5-4**). After recompletion, the well was pumped extensively and then sampled for analytes of concern. The average fluoride concentration decreased to 4.7 mg/L and pH decreased to 9.1. Subsequent blending of water from well TMWS #2 with water removed from the Alluvial Aquifer wells TMWS #1 & #3 resulted in a municipal water supply with fluoride concentration less than 1.0 mg/L, substantially below the MCL of 4 mg/L.

the fluid will conduct a current. It is one of the primary measurements used in water-quality tests to indicate levels of ion concentrations and thus quality of water. In this key well, specific conductivity of the shallow water zones is about 200 $\mu\text{S}/\text{cm}$ and specific conductivity in the lower zones, below 300 feet depth, ranges from 300-400 $\mu\text{S}/\text{cm}$ (**Fig 5-5**).

Geophysical data indicated lower resistivity (higher specific conductance) in sand intervals deeper than 300 feet. This information further indicated that water from the deeper Troublesome was the main contributor to undesirable water quality associated with the original well completion and explains why the recompletion was a success.

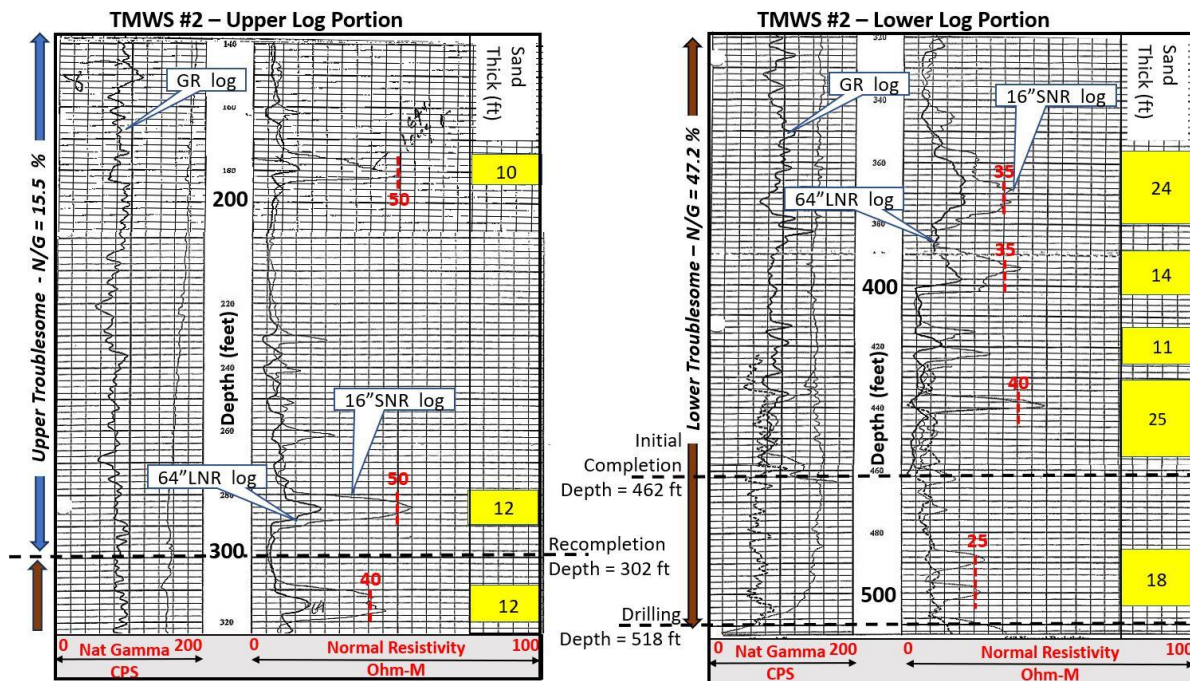


Figure 5-5. Geophysical logs from the TMWS #2 well with interpreted sand units (sand footage thickness and vertical extent shown in yellow boxes) encountered within the Upper and Lower Troublesome Aquifer. The resistivity logs provide specific depths and thickness of sand units as well as indications of water quality. For relatively fresh groundwater environments, the highly resistive zones correlate to clean sands within the lower resistive silt or clay intervals. The resistivity values for water sands measured from the 16" short normal resistivity (SNR) log are shown as short, dashed lines with annotated values. The highest resistive sands are in the upper portion of the well, less than 300 feet deep, indicating purer water. If more analytes, including metallic ions, dissolved solids, and other conductive compounds, are present in the groundwater, then water in the sand units becomes less resistive (more conductive). The lower portion of the well, greater than 300 feet deep, demonstrates less resistive sand units, therefore suggestive of increased analytes. The drilling lithologic log (**Appendix-Table A3-2a, A3-2b**) aided the interpretation of the sand units.

5.5 – Deep Troublesome Wells – Initial Review of Groundwater Water Quality Issues

5.5.1 - Well Geochemical Sample Comparisons

As discussed previously, water quality studies in the Fraser Valley concentrated on samples from the Alluvial Aquifer. Apodaca et al. (2000) provide a summary of water-quality data collected in 1998 from 20 wells within the Fraser Valley watershed (**Table 5-1**). The wells ranged in depth from 25 to 295 feet with an average of 106 feet. Field properties and concentrations of major ions from Apodaca (2000) are combined with a summary of geochemical properties from four deep Troublesome wells within this study area sampled from 2005 through 2023. These wells, labeled in the table as 8, 18, 14 and 12, have associated drilling depths of 295, 450, 518, and 595 feet, respectively. Well 14 is the “key” referenced TMWS #2 municipal well. Adding data from these deep wells allows comparison with the earlier Apodaca (2000) data. Most notable is the substantial increase in fluoride and sodium concentrations in the deep Troublesome wells. Water from two of the wells contain 2-3 times the USEPA maximum contamination level (MCL) of 4 mg/L (U.S. Environmental Protection Agency, 2009) for fluoride, indicative of potential adverse health effects. The USEPA has set the secondary contamination level (SMCL) for fluoride at 2 mg/L. The SMCL levels are defined as “cosmetic” levels by the USEPA. In addition, the total dissolved solids (TDS) show considerable increase in the deeper wells, with three of the wells screened in a higher pH (>8.0) environment.

One trace element that was not measured in the USGS study is arsenic (As). The USEPA MCL for arsenic is 0.01 mg/L (U.S. Environmental Protection Agency, 2009). Water from two of the wells (#8, #12) from shown on **Table 5.1** have arsenic concentrations greater than 0.02 mg/L. (There was no measurement taken for Arsenic associated with the deep Troublesome TMWS#2 well.) This high concentration of arsenic is twice the MCL for safe drinking water set by the USEPA. Arsenic, which can exist as As³⁺ and As⁵⁺ valence states, is more soluble under reducing conditions. High arsenic concentrations are more common at greater depths than oxidizing conditions near the surface. The most common occurrence of Arsenic is As⁵⁺, which is more easily removed from water.

Other notable trace elements have been detected in some well samples and include copper, lithium and uranium at moderately high levels. Where high values for pH, sodium and dissolved solids exist, the drinking water may have taste concerns compared to the Alluvial Aquifer sourced water. The USEPA has set pH levels of 6.5-7.5 as indicative of good water quality; values beyond that range would be in the SMCL category.

Table 5-1. Geochemical summary table for 20 Alluvial Aquifer and shallow Troublesome groundwater wells (Apodaca, et al, 2000) and four deep Troublesome Aquifer wells from this study. For comparative purposes, the table clearly demonstrates geochemical measurements of the benign freshwater associated with the shallow Alluvial Aquifer, whereas the deeper Troublesome wells have considerable increase in pH, fluoride, sodium, and dissolved

solids (color highlighted). Higher concentration of additional analytes not attempted as measurements in the Alluvial Aquifer but noted in the Troublesome groundwater include arsenic, copper, lithium, and uranium. Some of these recorded levels are well over the EPA maximum safe exposure limits.

USGS Report - WRI-99-4243, Apodaca, et.al, 2000					Deep Troublesome Wells			
Properties, constituents, and reporting units	Min	Median	Max	USEPA drinking-water standards or health advisories ^a	Well 8	Well 18	TMWS 14	Well 12
Well depth (ft)	25	106	295		295	450	518	595
Field properties								
Water temperature (°C)	6.0	7.8	14	---				20
Specific conductance (uS/cm)	106	236	436	---	210	428	400	
Oxygen, dissolved (mg/L)	0.1	4.5	7.6	---				
pH,field (standard units)	6.1	7.4	8.1	6.5-8.5 (SMCL)	9.04	7.7	9.5	8.17
Alkalinity (mg/L as CaCO ₃)	39	109	206	---	91	235	131	104
Turbidity (NTU)	0.06	0.42	3.17	5.0	0.2	4.0		
Major ions								
Bromide, dissolved (mg/L)	<0.01	0.02	0.06	---				
Calcium, dissolved (mg/L)	14.2	33.7	71.1	---		67.6		
Chloride, dissolved (mg/L)	0.33	1.78	16.4	250 (SMCL)	1.96	2.3		
Fluoride, dissolved (mg/L)	<0.10	0.19	1.40	4.0 (MCL)	0.737	0.10	12.3	7.47
Magnesium, dissolved (mg/L)	1.26	2.55	5.84	---	0.113	2.41		
Potassium, dissolved (mg/L)	1.03	2.00	6.30	---	0.743	1.40		
Silica, dissolved (mg/L)	11.1	28.1	46.6	---	20.0	23.3		
Sodium, dissolved (mg/L)	4.02	7.07	19.1	---	42.8	24.8		102
Sulfate, dissolved (mg/L)	1.62	3.14	10.9	250 (SMCL)	4.72	4.60		
Dissolved solids (mg/L)	82	129	281	500 (SMCL)	106	250	398	324
Arsenic (mg/L)	Not Measured			0.01 (MCL)	0.022	0.008		0.027
Copper (mg/L)	Not Measured			1.00 (MCL)	0.004	0.596		0.004
Lithium (mg/L)	Not Measured			0.01 (MCL)	0.02	ND		
Uranium (mg/L)	Not Measured			.030 (MCL)	0.003	0.0151		0.005

The Bauch and Bails (2004) USGS report documents additional statistical analyses and groundwater chemical classifications for 11 Alluvial Aquifer water wells within the Fraser Valley. These water samples were collected from 1998 through 2001. The data are presented on Piper Diagrams that categorize geochemical groundwater types (**Fig 5-6a-b**).

The dominant water type in the groundwater samples is calcium-bicarbonate (Ca-HCO₃) type water (Bauch and Bails, 2004) and data points clearly group on the far-central-left portion of the diagram (**Fig 5-6a**). These classes of water are typical of shallow, near-pristine fresh groundwater. With higher concentration of sodium in the deeper Troublesome Aquifer, the cluster of data points shifts to the bottom of the central Piper Diagram, as indicated by the red arrow.

Water Geochemistry Classification Comparison: 2000 USGS Study vs Current 2022 Study Geochemical Groundwater Types - Piper Diagrams

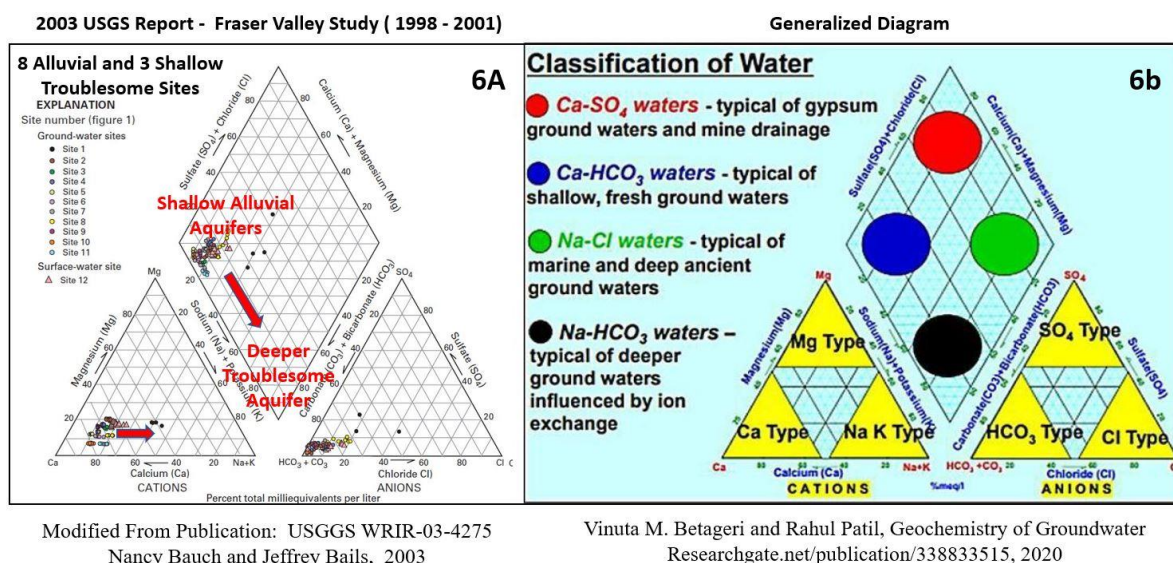


Figure 5-6a, 5-6b. Piper Diagram (6a) demonstrates the geochemical makeup of Alluvial Aquifer groundwater (Bauch and Bails, 2003) and a general Piper Diagram template (6b) (Betageri & Patil, 2020) to show the usefulness of Piper diagrams for groundwater classification.

5.5.2 - Deep Troublesome Wells – Water-Quality Issues

This study includes a water-quality data set for 18 wells within the Greater Pole Creek Basin. Five Alluvial Aquifer wells were installed at depths ranging from 58 to 160 feet. The remaining 13 wells extend into the Troublesome Aquifer at depths ranging from 174 to 725 feet. Two of these wells are listed in the USGS groundwater database; ([Water Resources of the United States—National Water Information System \(NWIS\) Mapper \(usgs.gov\)](https://waterresourcesoftheunitedstates.nwisis.usgs.gov/)). One is used for irrigation and the other is a domestic well. Three municipal wells and one associated recompletion well are part of the Tabernash Meadows Water and Sanitation District. Twelve private wells (locations confidential) are included in this data set and serve domestic; commercial or irrigation uses. A summary listing of all these 18 wells and associated geochemical measurements is provided in **Table 5-2**. (All water-quality data used for these analyses are available via USGS Science Data Catalog (Rosenberry and Stoughton, 2024).

Four common groundwater geochemical indicators were evaluated and graphed as a function of total well depth. These four indicators – specific conductance, total dissolved solids, pH, and fluoride – provide a general assessment of groundwater quality within the Greater Pole Creek Basin (**Figs 5-7 through 5-10**). All indicators increased in concentration with depth. Three reference depths, 200, 400, and 600 feet, are highlighted on the graphs and serve to define four subsurface intervals (<199 ft, 200-

399 ft, 400-599 ft and >600 ft). For comparison purposes, the median values and depths for the same shallow Alluvial Aquifer geochemical constituents derived from the USGS 20 well survey (**Table 5-1**, Apodaca, and others, 2000) are shown on the lowest row on **Table 5.2** and annotated on the graphs. Based on the trend lines for each geochemical indicator, geochemical concentrations can be estimated for a well drilled to various depths, along with a range of uncertainty (**Table 5-3**).

Specific conductance (SC) of the sampled groundwater is a measure of the collective concentration of dissolved ions in solution (USGS, 2019). The graph of specific conductance versus depth (**Fig 5-7**) clearly demonstrates the increasing ionic concentration for deeper wells within the Troublesome Aquifer. The set of electrical conductivity values derived from geophysical logs of TMWS #2 well (**Fig 5-5**) also shows similar conductivity trends with depth, providing greater confidence that increased concentrations of dissolved constituents exist in the deeper portion of the Troublesome Aquifer.

Total dissolved solids (TDS) are largely made up of inorganic salts along with a small amount of organic matter. Inorganic salts commonly found in groundwater include calcium, magnesium, potassium, and sodium, which are all cations, carbonates, nitrates, bicarbonates, chlorides, and sulfates, which are all anions. TDS values from 9 wells in the study area show an increasing concentration versus depth (**Fig 5-8**), similar to the conductivity trend. All but one sample is below the EPA secondary guideline threshold of 500 mg/L (EPA, 2009). In general, TDS concentration reflects the perceived taste of drinking water. Very low concentrations are considered as tasting “flat”, whereas moderate concentration below 500 mg/L have better reviews (Safe Drinking Water Foundation, 2023). Extremely high levels of TDS are considered bitter and metallic tasting. In addition, high values of TDS lead to scaling and staining of plumbing fixtures.

The pH of water is a measure of its acidity or alkalinity with a scale that ranges from 0 to 14, 7.0 being neutral. Like TDS, pH is a secondary standard for EPA; the Secondary Maximum Contaminant Level (SMCL) for pH is between 6.5 and 8.5. According to the U.S. Environmental Protection Agency, the noticeable effects of a pH that is less than 6.5 include a bitter, metallic taste and corrosion. The noticeable effects of a pH above 8.5 include slippery feeling, soda-like taste and associated mineral deposits. pH values below 6.5 can lead to dangerous water quality when combined with other compounds. Such water can leach metal ions, including iron, manganese, copper, lead and zinc from plumbing fixtures and pipes, causing health concerns as a water supply. Fortunately, most of the water samples from the Greater Pole Creek Basin indicate very good water within the optimum pH zone.

The trend line on the graph representing pH as a function of depth (**Fig 5-9**) is well within the EPA secondary guidelines. The trendline excludes 4 outliers, three that demonstrate substantially high pH values. These samples may be associated with localized conditions caused by isolated water that is particularly old, requiring additional study to fully understand.

Fluoride was analyzed for all 18 wells (**Fig 5-10**). Several fluoride values were obtained from the original municipal wells TMWS #2 and TMWS #2R recompletion that accessed deep Troublesome groundwater. Five of the 18 wells demonstrate substantially high levels of fluoride, ranging from 4.5 to 20 mg/L, all above the EPA MCL of 4 mg/L. These wells range in depth from 302 to 725 feet. Samples from the

remaining 13 Troublesome and Alluvial Aquifer wells indicate very low to moderate concentrations of fluoride, ranging from 0.1 to 3.50 mg/L (**Fig 5-10**). Samples from the five shallow Alluvial wells all indicate very low concentrations of fluoride, all below 0.5 mg/L. The graph of fluoride concentration versus depth (**Fig 5-10**) clearly shows increasing concentration with depth. Interestingly, 8 samples from the deeper Troublesome wells (greater than 300 feet) indicate low to moderate fluoride concentrations. These observations suggest that some deeper segments of the Troublesome Aquifer are not subject to increased fluoride concentrations. The differences may be attributed to the unique local geochemistry or the degree of interconnectivity within the aquifer. More groundwater sampling and subsequent studies are necessary to better define these geochemical distributions of fluoride.

High concentrations of fluoride in some of the deeper Troublesome wells may be indicative of elevated concentrations of other major ions that were not analyzed (McMahon, et al, 2020). Although not analyzed for this study, associated high values of arsenic, lithium, uranium, or copper would be a concern if present in drinking water extracted from the wells with elevated concentrations of fluoride.

There can be substantial uncertainty when extrapolating these data trends to other specific domestic or municipal wells installed within the Greater Pole Creek Basin. Outlier values are indicative of the possibility of water quality from a specific well that is substantially different from what would be indicated based on the statistical trend lines shown in **Fig 5-7, 5-8, 5-9, 5-10**. Furthermore, many wells produce water from multiple depths, producing water with mixed geochemistry. Another uncertainty of associating chemical concentrations with depth is the variable datum from which depth to sampled water is determined. This study assumes depth below land surface, but the water table could also be a reasonable datum.

Uncertainty for values presented in **Figs 5-7, 5-8 and 5-10** is 10 percent of the maximum value. In the case of pH, the uncertainty indicated in **Fig. 5-9** is +/- 10 percent of the difference between the smallest and largest measured values. The trend lines in **Fig 5-7, 5-8, 5-9, 5-10** are based on a relatively small sample size and should be considered a first approximation of constituent concentration with depth. With additional water-quality analyses, the uncertainty will decrease, and specific anomalous areas may be identified.

Chemical constituents for all 18 sampled wells are presented in **Table 5-3** with values for each 100-foot depth increment derived from the best-fit trend lines. The estimated uncertainties for each of the geochemical projected concentration versus depth are also noted at the bottom of the display. The range of uncertainty for each geochemical concentration is based on a limited data set, but with more data the uncertainties can be refined.

Table 5-2. Well use type, aquifer of emplacement, total well depth, and selected water-quality parameters for 18 wells installed in the Greater Pole Creek Basin collected for this report (upper portion of table). The lowest row of the table (within red box) shows a composite summary of 20 shallow wells within Fraser Valley with same water quality parameters referenced in USGS report wri-99-4243 (Apodaca, et al, 2000) inclusive range and median values of measured concentrations. Conductivity = specific conductance at 25°C., TDS = total dissolved solids.

Table of Geochemical Properties from Well Sample Tests

Study Well Number	Well Name USGS Site Name	Use	Aquifer name	Total Well Depth feet	Conductivity $\mu\text{S}/\text{cm}$	TDS mg/L	pH pH	Fluoride mg/L
1	SC00107604ABC	Irrigation	Troublesome	295	292	202	7.81	0.10
2	TMWS #3	Municipal	Alluvial	64			7.38	0.21
3		Commercial	Alluvial	160				0.32
4		Domestic	Alluvial	120			7.50	0.45
5	TMWS #1	Municipal	Alluvial	58			7.60	0.40
6	SC00107602DAC	Domestic	Alluvial	120	263	172	6.76	0.45
7		Commercial	Troublesome	174			7.70	1.08
8		Domestic	Troublesome	295	210	106	9.04	0.74
9	TMWS #2 R	Domestic	Troublesome	475				3.00
10		Commercial	Troublesome	200			7.80	3.50
11		Municipal	Troublesome	302			9.10	4.74
12	TMWS #2	Irrigation	Troublesome	595		324	8.17	7.47
13		Domestic	Troublesome	600	890	540	8.06	14.10
14		Municipal	Troublesome	518	400	398	9.50	12.30
15	TMWS #2	Domestic	Troublesome	725				20.00
16		Domestic	Troublesome	325	351	205	7.90	0.10
17		Domestic	Troublesome	392	375	219	7.90	0.10
18		Domestic	Troublesome	450	428	250	7.70	0.10
20 Wells	USGS report WRI-99-4243	Various	Alluvial & Troublesome	25-295 106 (med)	106-436 236 (med)	82-281 129 (med)	6.1-8.1 7.4 (med)	<0.10-1.40 0.19 (med)

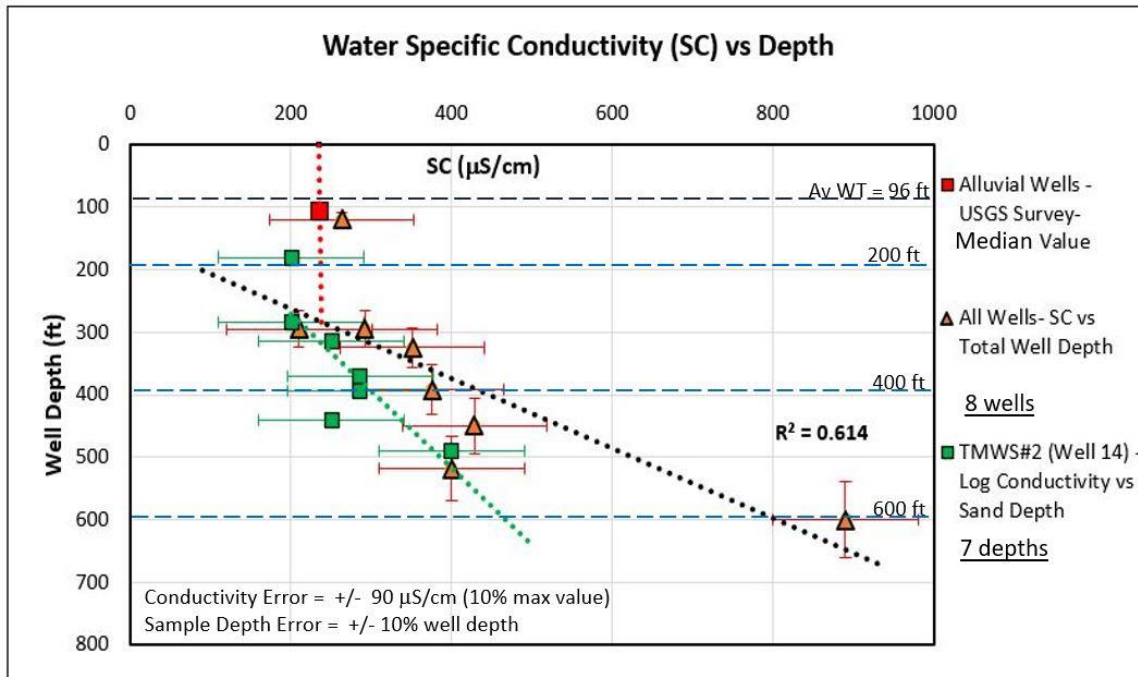


Figure 5-7 Graph of specific conductivity (SC) measurements as a function of depth from available groundwater samples taken from 8 municipal and domestic wells within the Greater Pole Creek Basin (orange-triangle markers). The data values from wells increase with greater depths into the Troublesome Aquifer. Black dashed line is a best-

fit trendline of SC vs depth for the 8 wells. Uncertainty-error bar indicators are also displayed on the graph. For reference purposes, the median value of this measured attribute taken from 20 shallow Alluvial Aquifer groundwater wells (**Table 5-1, Table 5-2** / Apodaca, et al, 2000) are depicted on the graph (red-square marker). Seven derived conductivity measurements from the TMWS #2 well log are displayed (green-square marker) along with the best-fit trend line for the log conductivity displayed as a green dashed line.

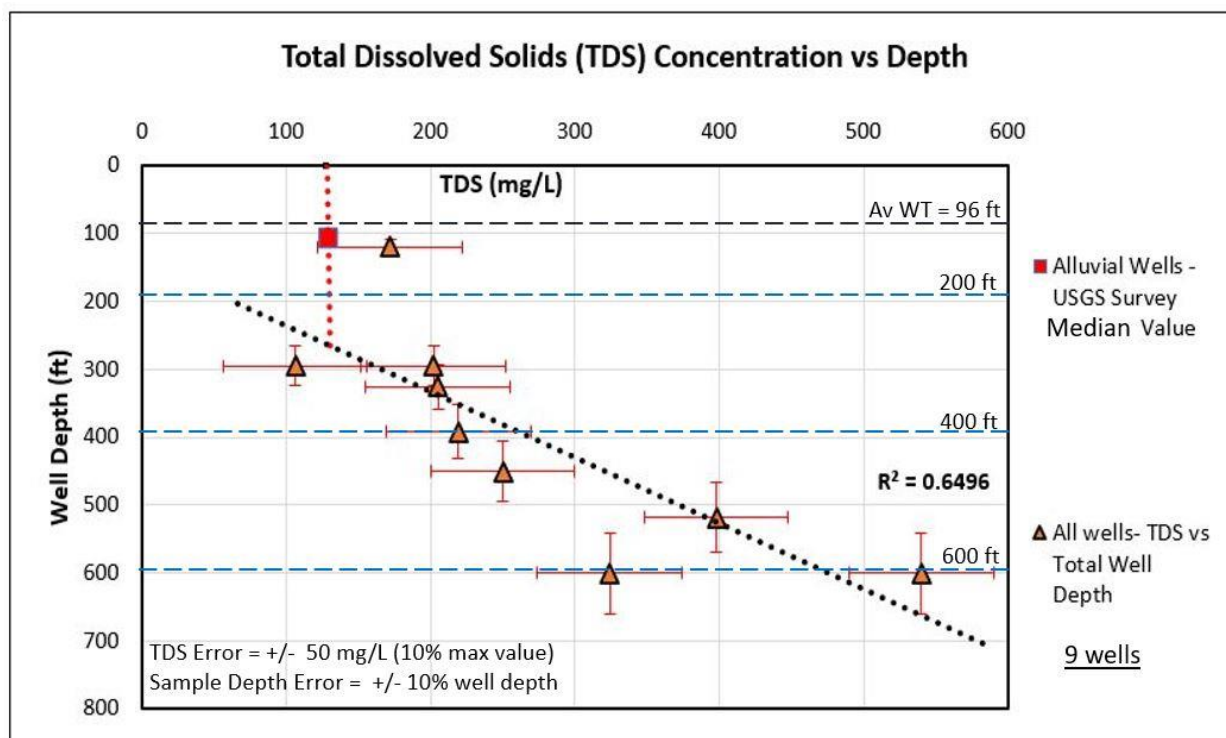


Figure 5-8. Graph of total dissolved solids (TDS) concentration as a function of depth from available groundwater samples taken from 9 municipal and domestic wells within the Greater Pole Creek Basin (orange-triangle markers). The data values from wells increase with greater depths into the Troublesome Aquifer. For reference purposes, the median value of this measured attribute taken from 20 shallow Alluvial Aquifer groundwater wells (**Table 5-1, Table 5-2** / Apodaca, et al, 2000) are depicted on the graph (red-square marker). Black dashed line is a best-fit trendline of TDS vs depth for 9 wells. Uncertainty-error bar indicators are also displayed on the graph.

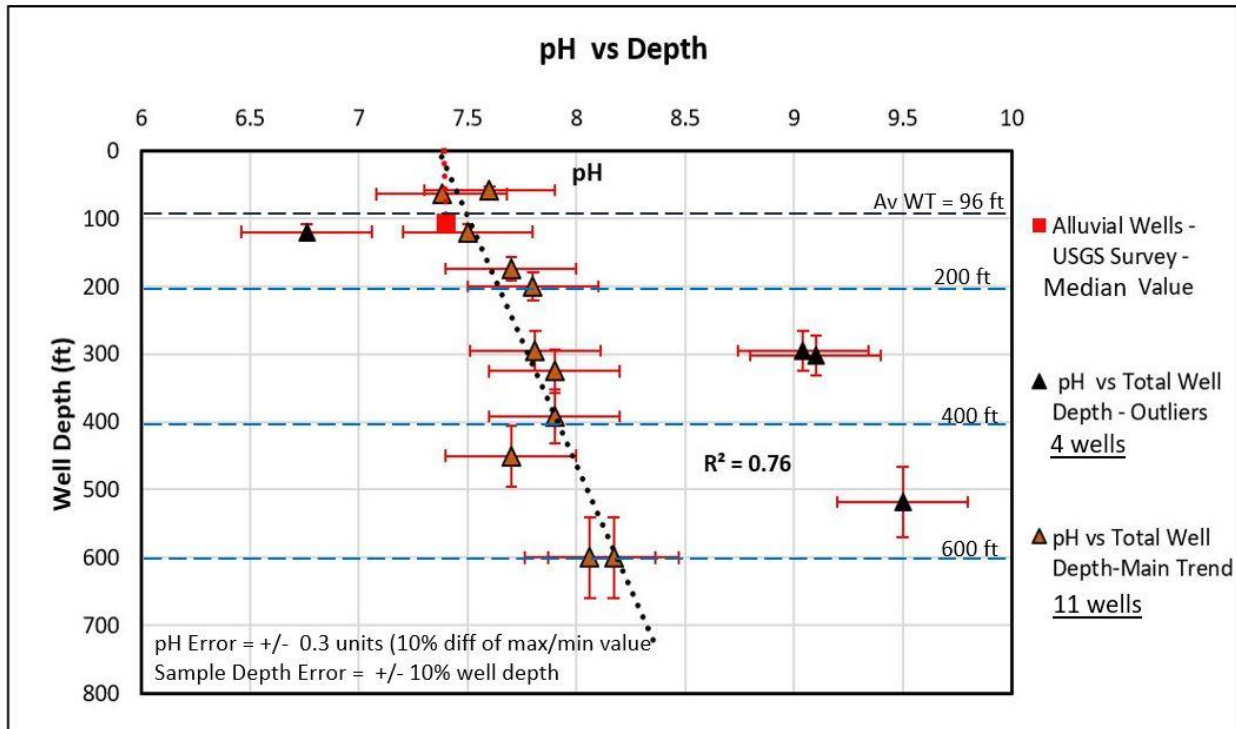


Figure 5-9. Graph of pH as a function of depth from available groundwater samples taken from 15 municipal and domestic wells within the Greater Pole Creek Basin (orange triangles). The median value taken from 20 shallow Alluvial Aquifer groundwater wells (Table 5-1, Table 5-2 /Apodaca, et al, 2000) is indicated with the red square). Black dashed line is a best-fit trendline of pH vs depth for 11 wells. Uncertainty-error bar indicators are also displayed on the graph. The statistically derived trend line excludes 4 outliers indicated by black triangles. Uncertainty-error bar indicators are also displayed on the graph.

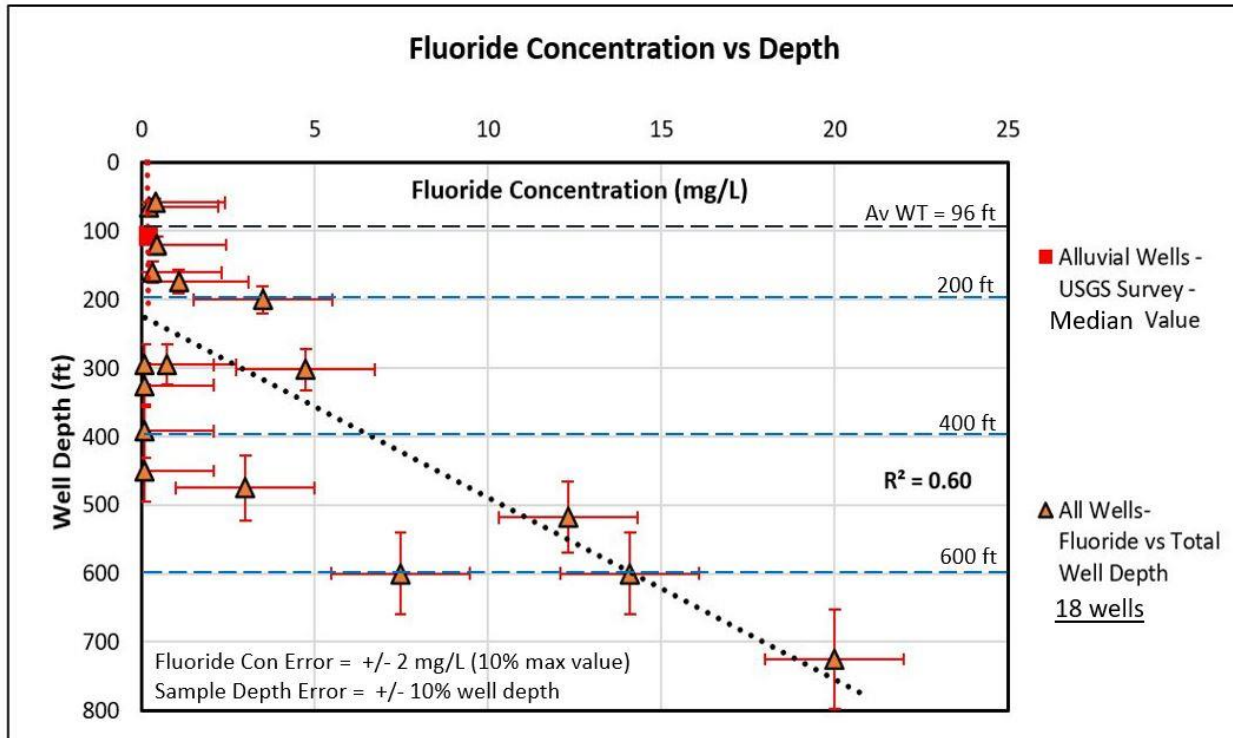


Figure 5-10. Graph of fluoride (F) concentration as a function of depth from 18 municipal and domestic wells within the Greater Pole Creek Basin (orange triangles). The median value of fluoride taken from 20 Alluvial Aquifer wells (Table 5-1, Table 5-2 / Apodaca, et al, 2000) is depicted by the red square. Black dashed line is a best-fit trendline of fluoride vs depth for 18 wells. Uncertainty-error bar indicators are also displayed on the graph.

Table 5-3. Look-up table for geochemical concentrations of total dissolved solids and fluoride as well as the estimated values of specific conductivity and pH are provided as a function of well depths. Selected water-quality constituents versus depth with values taken from trend lines shown on **Figures 5-7, 5-8, 5-9, 5-10**. Ranges of uncertainty are also noted at the bottom of the chart under each constituent.

Greater Pole Creek Basin - Troublesome and Alluvial Aquifers

Geochemical Concentration / Attribute at Various Well Depths

Well Depth (Feet)	Specific Conductivity (μ S)	Total Dissolved Solids (mg/L)	pH (unit)	Fluoride (mg/L)
100	220	120	7.45	0.1
200	230	150	7.60	0.1
300	250	180	7.75	3.0
400	420	280	7.90	6.5
500	610	380	8.05	10.0
600	800	480	8.20	14.0
700	990	580	8.35	18.0
800	1080	680	8.50	22.0
Est Uncertainty	+/- 90	+/- 50	+/- 0.3	+/- 2.0

This study includes integrating 260 wells that range in depth from 45 to 1100 feet with an average depth of 356 feet. The reference map (**Fig 5-11**) depicts the surface position of these wells. The well location symbols identify four well-depth intervals (less than 200 ft, 200-399 ft, 400-599 ft) and correspond to the same depth intervals shown on the geochemical attribute graphs (**Fig 5-7, 5-8, 5-9, 5-10**). This map reflects the distribution and density of domestic groundwater wells that are subject to increased geochemical concentration according to the depth segments illustrated by shape-color designations. In addition, the non-confidential TMWS #1, #2, #3 municipal wells that document fluoride concentrations are shown.

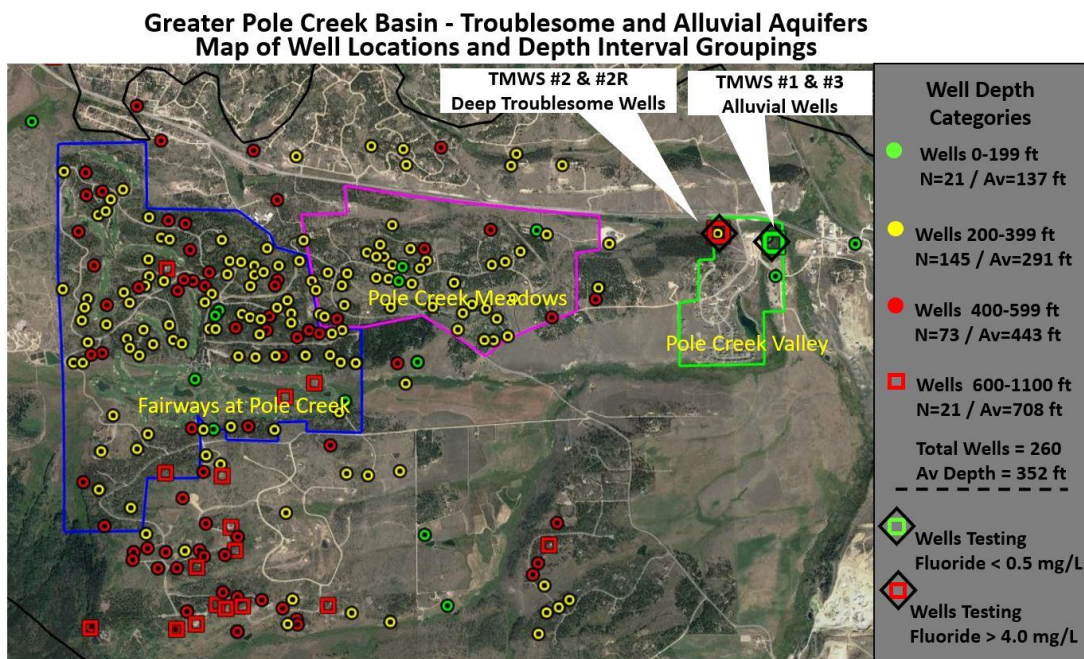


Figure 5-11. Location map of 260 groundwater wells considered in this study that are color-shape coded into four depth groupings as depicted on graphs of geochemical attributes and concentrations (Fig 5-7, 5-8, 5-9, 5-10). The number of wells within each group is noted on the map legend. The map also denotes the location of key non-confidential municipal wells with recorded fluoride concentrations.

A plot of land-surface elevation versus well depth elevation shows the distribution of well-depth elevations relative to the east-west slope of the valley and further demonstrates the increase of groundwater specific conductance, TDS, pH, and fluoride concentration with depth.

In general, the oldest groundwater is to the right, at the lowest part of the basin where groundwater discharges to surface water. Troublesome wells with fluoride concentrations greater than 4 mg/L are situated in this area. This is not a uniform progression of groundwater age, however, as geologic heterogeneity also substantially affects the spatial distribution of water-quality concentrations and groundwater age.

Greater Pole Creek Basin - Troublesome and Alluvial Aquifers

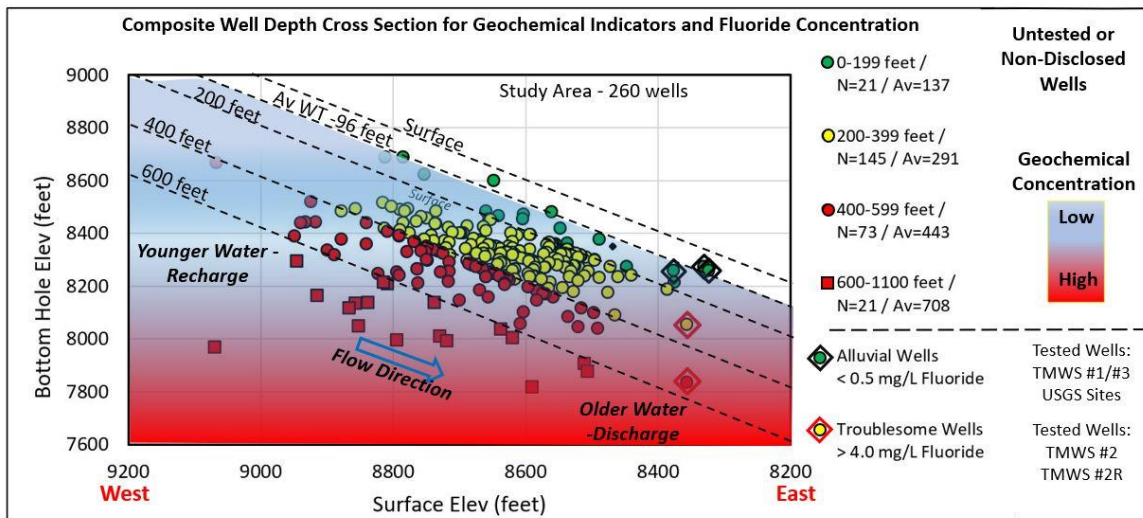


Figure 5-12. A composite well data diagram demonstrates well bottom hole and surface elevations of 260 wells incorporated into the study. The diagram is a general proxy for a west to east (left to right) cross-section of the Greater Pole Creek Basin and illustrates, via color variation, the general groundwater quality with increasing depth. Wells are grouped into four depth categories and are tied to the same depth categories shown on the geochemical attribute and concentration graphs (Fig 5-7, 5-8, 5-9, 5-10). The color and shape of the markers are the same as that indicated in Fig 5-11.

5.6 - Implications for Homeowners

Water quality within the Troublesome Aquifer is greatly variable and testing water quality of individual domestic wells is not regulated or mandatory. Therefore, it is up to the homeowner to determine the chemical quality of groundwater removed from each domestic well. Water-quality samples are relatively easy to obtain, and many certified labs can provide water-chemistry analyses. If some chemical constituents exceed EPA-recommended thresholds, a filter system can often be designed to reduce concentrations of specific constituents. These systems can be either point of use (POU), such as a kitchen sink, or whole house point of entry (POE). In addition, these filters would condition/soften the water for better taste and home use.

6 - Conclusions

Even though there has been a decrease in precipitation to recharge the Troublesome Aquifer, analysis of existing data indicates an ample supply of groundwater for domestic use still exists within the Upper Pole Creek Basin, including The Fairways at Pole Creek and Pole Creek Meadows Developments. Projections for continued drought and increased water consumption indicate that water supplies will remain sufficient for at least the next 25 years.

One concern for the upper portion Troublesome Aquifer is the relatively slow rate of water flow through the aquifer due to extensive silt deposits. In addition, minor faults may serve as partial barriers and may affect the water flow. These two factors may impact water-well production and, therefore, extended periods with high rates of well pumping should be minimized. Reducing rates of water use or adding supplemental water storage can also minimize concerns of low well yield. Concerned homeowners could obtain more information from their drilling contractor.

Past water-quality studies focused primarily on Alluvial Aquifer wells in the central portion of the Fraser Valley. Since those earlier studies, hundreds of deeper domestic wells have been completed in the Troublesome Aquifer, especially within the Greater Pole Creek Basin. The geochemical properties for deep Troublesome water are considerably different than shallower alluvial water. These variations are mainly due to variable aquifer hydraulic properties and variable age of the water. The few deep Troublesome Aquifer wells with publicly available data indicate much higher levels of ions and trace elements, some of which exceed the EPA standards for safe drinking water. Because concentrations of water-quality constituents in the Troublesome Aquifer vary substantially over the study area, comprehensive analyses of water supplied by homeowner wells may be warranted, which would indicate whether water filtering may be required.

Other areas within the Fraser Valley may also benefit from comprehensive hydrological and hydrogeological reviews. Specifically, aquifer characteristics, reliance on surface water versus groundwater, and the impact of large-scale water diversions are factors that require quantitative assessment in any developed mountain valley. All communities would benefit from determination of the volume, availability, and quality of the associated water resources. This information will also allow projection of water-resource availability in response to various stressors and drivers.

6.1 Considerations for Future Work

6.1.1 Water-table monitoring wells

Development of maps for this study identified areas where installation of water-table monitoring wells would improve understanding of aquifer characteristics and associated groundwater availability and quality. Automated collection of time-series water-level data would allow quantification of changes in

aquifer water levels and associated groundwater storage. As a start, two locations have been identified in this study.

6.1.2 Additional mapping

Additional water-table mapping should be considered using subsets of wells with water levels measured during low runoff periods of July-December and wells measured during high run-off period January-June. Difference maps can then be derived to possibly assess magnitude of annual water-table variations throughout study area.

6.1.3 Additional Well Pump Test Data

Additional aquifer pumping tests would provide better understanding of aquifer hydrogeological properties.

6.1.4 Groundwater flow modeling

Data summarized with this study could provide better calibration for future groundwater-flow models designed to study the flow dynamics of the Upper Troublesome Aquifer in response to projected recharge, drought, and projected groundwater withdrawals. Emphasis could be placed on investigating the effects of minor faults on flow dynamics.

6.1.5 Develop a comprehensive water budget.

This study combined data from several sources to generate a preliminary water budget for the Greater Pole Creek Basin. The scenario, described in detail within **Section 3.7** and summarized in **Figures 3-14a and 3-14b**, represents two deterministic results, the most likely and reduced-water-availability cases, respectively. Additional water-budget-related efforts should include a probability range for each variable as well as links to interrelated dependencies. In addition, changing precipitation and temperature trends should be considered. Monte-Carlo or similar statistical analyses could generate results that would be statistically more realistic with quantifiable probabilities of occurrence. The process could be tailored for specific “what if” scenarios.

6.1.6 Additional Water-Quality Assessments

A more comprehensive water-quality survey would better quantify water-quality variability within the study area and also the portion of the Fraser Valley that relies on water derived from the Troublesome Aquifer. Assessment of the age of groundwater within the upper and lower portions of the Troublesome Aquifer could be correlated with water-quality analyses.

6.1.7 Other Fraser Valley Aquifer Assessments

Each watershed in the Fraser Valley has its unique set of aquifer characteristics, surface-water networks, water quality and water-use variables. Some of these watersheds are impacted by water diversion as part of the Moffat water diversion system (Army Corp of Engineers-Environmental Impact Study, 2014). A comprehensive effort could improve understanding of balancing dynamics of the aquifer and surface-water resources versus future consumption needs, particularly when water shortages or water-quality issues may occur. These may include contamination of surface water due to wildfire and/or increased water diversions. Uncertainty risk analyses can be performed with various scenarios tested with relative probabilities of occurrence. Appropriate contingency planning can then be made based on these quantitative analyses.

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Appendix – Figures

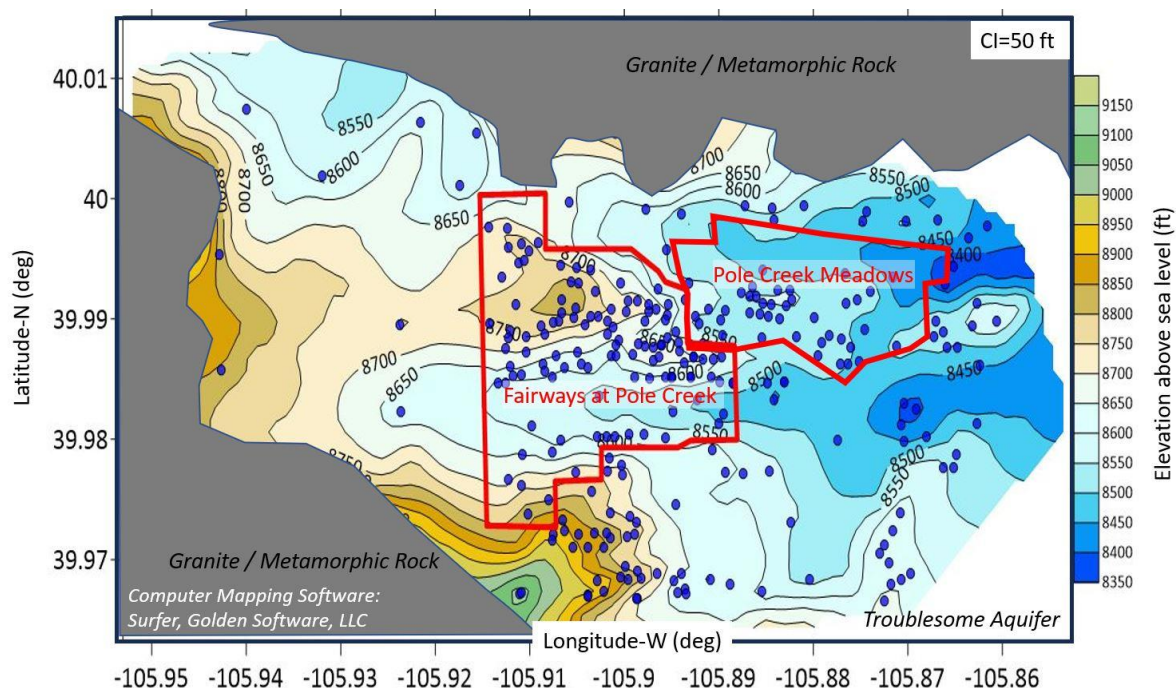


Figure A2-1. Surface Elevation Map covering the Greater Pole Creek Basin with corrected surface elevation well data that was incorporated in this study. The colored contour map corresponds to the extent of the Troublesome Formation within the basin. The darker shaded western and northern portion of the map relates to the much higher granite/crystalline rock mountains that provide the main watersheds. The map shows a prominent topographic ridge traversing west to east through both Fairways at Pole Creek and Pole Creek Meadows Developments. It is flanked by key low valley streams, Pole Creek to the south and Fisher Creek to the north.

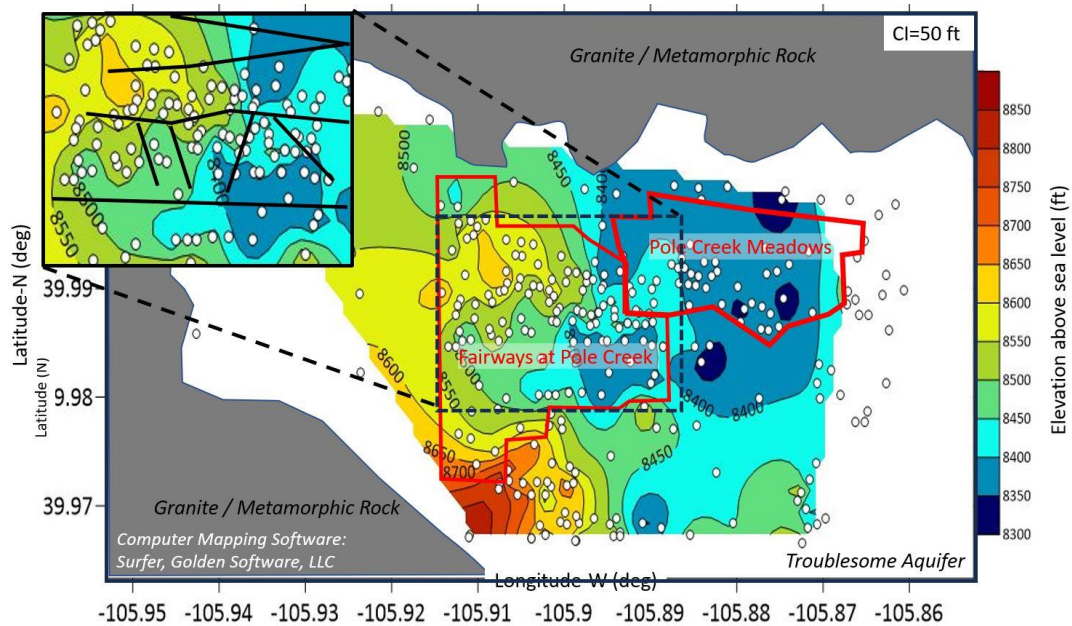


Figure A2-2. Uppermost Saturated Sand Elevation Map generated with computer mapping algorithms. The map was derived with wells having good quality drilling logs which specify sand intervals and depths. Both the contours and colored intervals on the map represent the same elevations. The map has discontinuities suggestive of minor faults as shown on the expanded section and discussed in detail within **Section 2.2**.

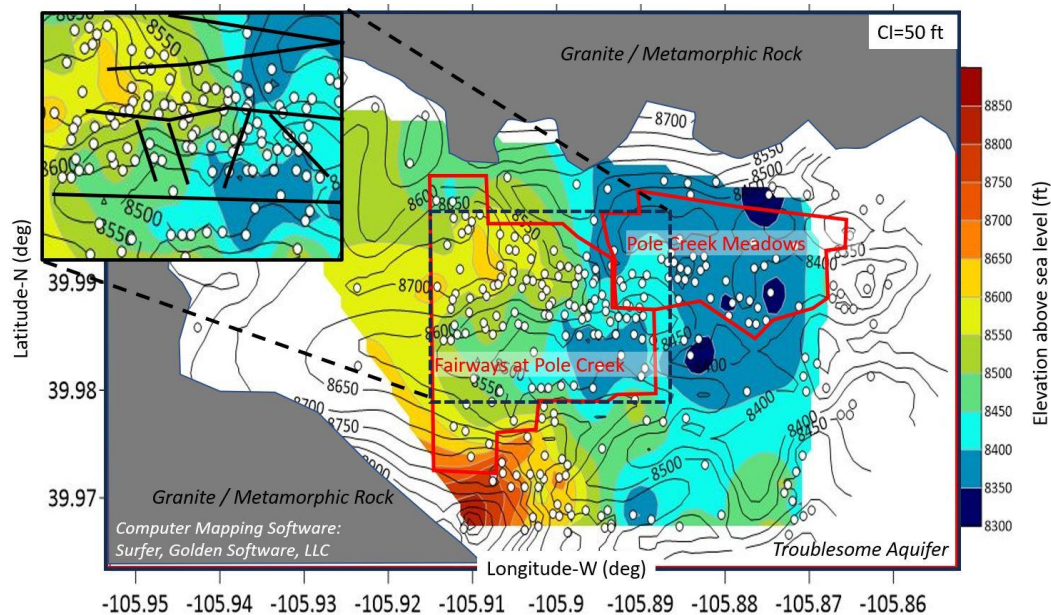


Figure A2-3. Comparison of the Uppermost Saturated Sand Elevation Map (color) and Surface Elevation Map (contours). Both maps were generated with computer mapping algorithms and are the combination of maps shown on **Fig A2-1** and **Fig A2-2**. The Sand Elevation Map does not exactly mimic the Surface Elevation Map but has

similarities. Both maps have discontinuities suggestive of minor faults as shown on the expanded section and discussed in detail within **Section 2.2**.

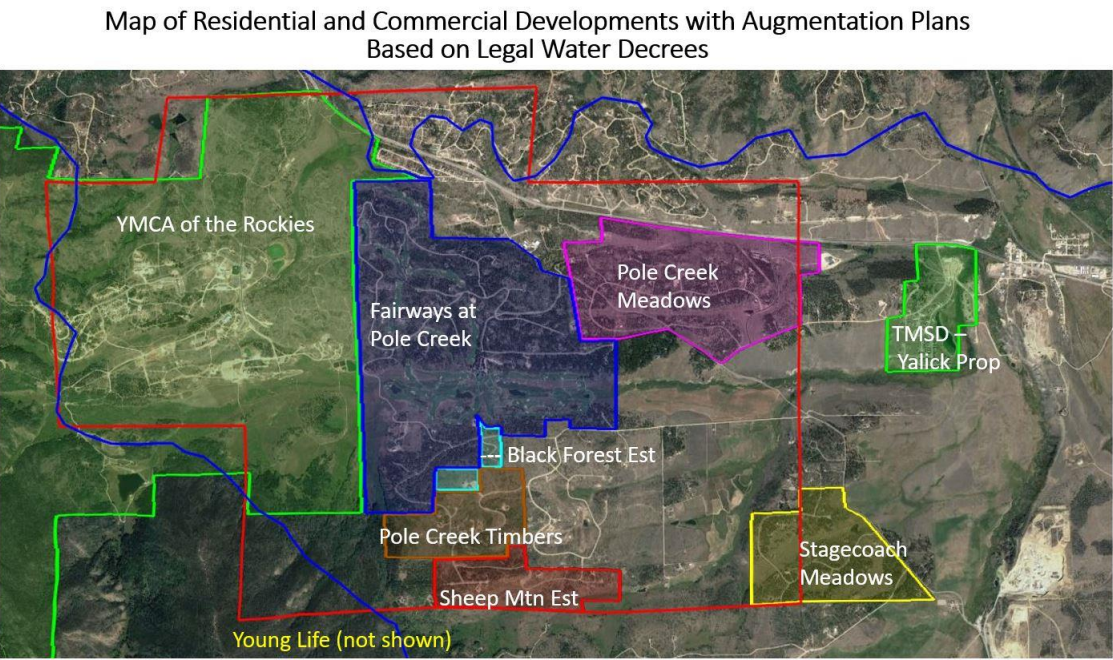


Figure A3-1. Map of residential and commercial development properties with decreed water augmentation plans within the Greater Pole Creek Basin and corresponds to those listed on **Appendix Tables A3-1a** and **A3-1b**.

State Engineering Office (SEO) Correspondence

Documents associated with most recent position on Upper and Lower Troublesome differentiation status

2a

From: Lis, Craig
Sent: Wednesday, August 28, 2002 4:34 PM
To: Smilovits, Shana; Whitaker, Kyle
Subject: 01CW176, Tabernash Water & Sanitation District

Here are my comments on the engineering report.

1) Blatchley report; Curt Wells letter of February 11, 1999 and Memorandum of March 22, 2002. The estimated delayed depletions are based on outdated information. The stipulation in Case No. 80CW67 (cons. w/ Case Nos. 80CW456 & 84CW175) assumes that the Troublesome Formation was divided into upper and lower aquifers. This was based on a shale layer evident in the logs for two deep wells, one of which was the YMCA non-tributary well. Review of other well logs since that time has indicated that there is no evidence that the shale layer exists elsewhere in the formation. In fact, review of the decree in said cases indicates that our position had changed between the signing of the decree and the case, since replacements to Pole Creek above and below the development are required, in contrast to the stipulation which required replacement only to the Fraser River. Therefore the applicant must estimate depletions to Pole Creek and other nearby streams.

Portion of Memo from SEO Representative Related to
Tabernash Water & Sanitation Well Decree (01CW176)

State Engineering Office (SEO) Correspondence

2b

Documents associated with most recent position on Upper and Lower Troublesome differentiation status

- Is there a depth or stratigraphic limitation set by the State Engineers to permit and drill into the Lower Troublesome Aquifer?
 - No, in general there is no depth or stratigraphic limitation to drill into the Lower Troublesome Aquifer under an exempt well permit. If production of a non-exempt well was limited to a specific aquifer (e.g. Lower Troublesome Aquifer) per its respective decree, then there could be a situation where the Hydrogeology section of our office would conduct a site-specific analysis to determine the interval of the specific aquifer that the well was limited to producing from per its respective decree.
- If not, then if a homeowner deems necessary, apply for a standard drilling permit to drill a new or deepen an existing well without any legal impairments?
 - Yes, a homeowner could apply for a permit to replace/deepen an existing well, which may limit production of the replacement well to a specific aquifer per its respective decree.
- If there are any state legal restrictions for domestic wells drilling the Lower Troublesome Aquifer, could you please have the State Engineers provide a reference document or formal statement regarding such restrictions?
 - I am unaware of any state legal restriction for drilling a domestic well into the Lower Troublesome Aquifer under an exempt well permit. As referenced above, production of a non-exempt well may be limited to a specific aquifer per its respective decree.
- Do the State Engineers regard the Lower and Upper Troublesome Aquifers hydrologically separate units? (Lower Aquifer being confined)?
 - I do not believe the State Engineer regards the Lower and Upper Troublesome Aquifers as hydrologically separate units, but rather views them together as the Troublesome Aquifer.

D Stoughton Personal Correspondence: Letter response excerpt from
SEO representative, Caleb Foy, P. E., Assistant Div Engineer, Water District 5 - dated 2/2/2022

Figure A3-2a, A3-2b. Correspondence from the Colorado State Engineering Office (SEO) regarding the connectivity of the Upper and Lower Troublesome Aquifers. Based on the interpretation of well data, the SEO notes there is no apparent wide-spread confining impermeable unit separating the two aquifers and therefore both are considered unconfined and hydraulically pressure connected. This study has interpreted additional more recent well data and has reached the same conclusion. Additionally, this study has documented the two aquifers having different overall hydraulic flow and geochemical properties. Subsequent use of the water resources from one or both units should take these differences into account.

Appendix – Tables

Table A1-1a and A1-1b. Summary of parameters used and results for statistical estimations of water volume(s) yield for the Upper and Lower portions of the Troublesome Aquifer within the Greater Pole Creek Basin. Parameters were taken from well data summary (**Table 1a, 1b**), weighted average specific yields (Sy) based on sand Sy, silt Sy and net/gross (**detailed in Section 1.4.1**) and one average area (**Section 1.4.2, Fig 1-11, Table 1-2**). All calculations are based on the unconfined status of the Upper and Lower Troublesome and thickness measurements of saturated intervals below the water table. Upper Troublesome volume results shown are for a 400 ft reference drilling depth scenario. The Lower Troublesome volume has been based on a 170 ft gross thickness.

1a

Upper Troublesome – Reference 400 ft Depth Drilled			
	Low Case	Input Av Case	High Case
Area of Aquifer Extent for Volume Calculation (acres from map) =		4888	
Reference Total Drilling Depth for Volume Calculation (ft) =		400	
Specific Yield of Sat Sand Interval (Percent)	24.0%	26.0%	28.0%
Specific Yield of Sat Non-Sand Interval (Percent)	5.0%	7.5%	9.0%
Sat Int Data Derived Directly From Well Log Data (U Troublesome Aquifer)			
	Low Case / P(10)	Av Case / P(50)	High Case / P(90)
Total Thick of Sat Interval above Ref Depth (ft)	242	304	366
Thick of Sat Porous Sand Interval above Ref Depth (ft)	1	18	36
Thick of Sat Non-Sand Interval above Ref Depth (ft)	226	285	345
Sand vs Entire Interval Ratio (Net/Gross) (Percent)	0.6%	6.0%	11.3%
Water Volume Calculations (Upper Troublesome Aquifer- acre-ft)			
	Low Case / P(10)	Output Av Case / P(50)	High Case / P(90)
Total Volume of Saturated Interval =	1,183,544	1,485,615	1,787,686
Water Vol Yield for Porous Sands =	1,769	23,122	56,809
Water Vol Yield for Non Sand Int =	58,809	104,751	142,632
Total Water Vol Yield for Saturated Interval = acre-feet	60,578	127,873	199,441
Specific Yield for Entire Interval (Percent)	5.1%	8.6%	11.2%

Average Case

1b

Lower Troublesome – 170 ft interval drilled to various depths			
	Low Case	Input Average	High Case
Area of Aq Extent for Vol Cal (acres) = 80% of U Troublesome(Av Case)	3422	3910	4399
Total Thickness (feet)	120	170	220
Net Sand to Gross Thickness Ratio (N/G) (Percent)	29%	41%	53%
Specific Yield of Sat Sand Interval (Percent)	24%	26%	28%
Specific Yield of Sat Non-Sand Interval (Percent)	5%	7%	9%
Sat Int Data Derived Directly From Well Log Data (L Troublesome Aq)			
	Low Case	Average	High Case
Total Thickness of Saturated Interval (ft)	120	170	220
Thickness of Sat Porous Sand Interval (ft)	35	70	117
Thickness of Sat Non-Sand Interval (ft)	85	100	103
Sand vs Entire Interval Ratio (Net/Gross) (Percent)	29%	41%	53%
Water Volume Calculations (Lower Troublesome Aquifer- acre-ft)			
	Low Case	Output Average	High Case
Total Volume of Saturated Interval =	410,592	664,768	967,824
Water Vol Yield for Porous Sands =	30,959	70,864	133,366
Water Vol Yield for Non Sand Int =	20,406	27,455	31,841
Total Water Vol Yield for Saturated Interval = acre-feet	51,365	98,319	165,208
Specific Yield for Entire Interval (Percent)	12.5%	14.8%	17.1%

Average Case

Table A1-2. Comparative table of parameters for estimating groundwater resources within the Troublesome Aquifer from this study and from the Bishop-Broghden Assoc report (BBA Water Consultants, 1997-1998). This study breaks the Troublesome Aquifer into upper and lower intervals, each with different sand content and hydraulic properties, along with the volume summations of the intervals, whereas the BBA report considers both units as a single aquifer with one set of representative parameters.

Upper and Lower Troublesome Volume Parameters Used					← Direct Comparison →	Observations and Comments
Reference Date	Current Study 2022 Revised	Current Study 2022 Revised	Current Study 2022 Revised	BBA Fairways Report 1997 Original		
Drainage Basin(s)	Pole Crk, Thomas Crk, Fisher Crk			Pole Crk, Skunk Crk		• Different drainage basins
Aquifer Investigated	U Troublesome Only	L Troublesome Only	U&L Troublesome	U&L Troublesome		• Similar areal extent
Type of Reservoir	Unconfined	Unconfined	Unconfined	Unconfined		• Current study over 4 times number of wells evaluated
Extent of Troublesome Aquifers (acres)	4,888	3,910	4,888	4,780		• Similar overall total drilling depth
Number of Wells - Data Base	145	2	147	33		• Two times the depth to water table
Well Density (wells per sq mi)	0.030	0.001	0.030	0.007		• Current study breaks up the Troublesome into two different units with different properties
Well Depths Included in Study	67-1100	600-630	67-1100	46-630		• Current study has nearly 2 times total saturated thickness
Gross Thickness (Ref Drilling Depth-ft)	400	170	570	600		• Current study attributes 50% less specific yield to saturated interval
Depth to Static Water Level (Av-ft)	96	12	96	48		• Overall available water volumes nearly the same
Depth to Static Water Level (Range)	34-158		34-158	15-140 ft		
Thickness of Sat Sands (Av-ft)	18	70				
Range Thickness Sat Sands	1 - 35	35 - 117				
Thickness of Non Sand (Av-ft)	285	100				
Range Thickness Sat Sands	226-345	85 - 103				
Total Saturated Thickness (Av-ft)	304	170	474	246		
Sat Thickness (Range)	242-366	120-220	362-586			
Effective Water Bearing Zones (Av N/G)	6.0%	41.0%	10.5%	41.0%		
Effective Water Bearing Zones (Range)	0.6%-13.3%	29%-53%	7.0%-13.2%			
Specific Yield / effective porosity (Av%)	8.6%	14.8%	10.5%	20.0%		
Specific Yield / effective porosity (Range)	5.1%-10.9%	12.5%-17.1%	7.0%-13.2%			
Volume of Sat Thickness (Av-ac-ft)	1,485,615	664,768	2,150,383	1,175,880		
Volume of Sat Thickness (Range)	1.2E6 - 1.8E6	4.1E5 - 9.7E5	1.1E6 - 3.6E5			
Volume Available Water (Av-ac-ft)	127,873	98,319	226,192	235,176		
Volume Available Water (Range)	0.6E5 - 2.0E5	0.5E5 - 1.7E5	1.1E5 - 3.6E5			
Volume Den of Available Water (acft/sq mi)	26.2	25.1	46.3	49.2		

Table A1-3a, A1-3b, A1-3c. Comparative summary table of aquifer parameters and estimated groundwater resources from this study (3a) versus two previous USGS reports. The two USGS reports were inclusive of both the Alluvial and Troublesome Aquifers and incorporating the entire Fraser Valley (Apodaca and Bails, 1999 (3b) / Bauch and Bails, 2004 (3c). This study extended its investigation to measure areas of the Fraser Valley aquifer coverage and used assumptions from the Greater Pole Creek study to derive volumes for comparative purposes. As noted in **Section 1**, the emphasis of the previous reports was on water quality, not quantity, therefore specific parameters are very general, and volume estimates are incomplete or highly uncertain.

Reference Date	(Current Study)	Current Fraser Valley Study 2022	Current Fraser Valley Study 2022	Current Fraser Valley Study 2022
Drainage Basin(s)		Entire Fraser Valley	Entire Fraser Valley	Entire Fraser Valley
Aquifer Investigated		Alluvial Only	U Troublesome Only	Both
Type of Reservoir		Unconfined	Unconfined	Unconfined
Exent of Troublesome Aquifers (sq mi)		22.6	45.3	45.3
Exent of Troublesome Aquifers (ac)		14,484	29,009	29,009
Number of Wells - Data Base			145	147
Well Density (wells per sq mi)		0.000	0.005	0.005
Well Depths Included in Study		140	67- 1100	67- 1100
Gross Thickness (Ref Drilling Depth-ft)		0-140	500	500
Depth to Static Water Level (Av-ft)		10	96	10-100
Depth to Static Water Level (Range)				
Thickness of Sat Sands (Av-ft)		46	22	
Range Thickness Sat Sands				
Thickness of Non Sand (Av-ft)			356	
Range Thickness Sat Sands			319-440	
Total Saturated Thickness (Av-ft)		46	378	424
Sat Thickness (Range)			342-466	
Transmissivity (gpd/ft)		12000	5000	5759
Hydraulic Conductivity (ft/day)		34.9	1.8	1.8
Hydraulic Conductivity (cm/sec)		1.23E-02	6.24E-04	6.41E-04
Effective Water Bearing Zones (Av N/G)			6.0%	
Effective Water Bearing Zones (Range)			0.6%-11.3%	
Specific Yield / effective porosity (Av%)		20.0%	8.6%	9.3%
Specific Yield / effective porosity (Range)			5.1%-10.9%	
Volume of Sat Thickness (Av-ac-ft)		666,264	10,965,402	11,631,666
Volume of Sat Thickness (Range)				
Volume Available Water (Av-ac-ft)		133,253	943,836	1,077,089
Volume Available Water (Range)				
Volume Den of Available Water (acft/sq mi)		5,888	20,823	23,763

3a

Summary of Current Study

Parameters Used for Fraser Valley
In-Place and Accessible
Water Volumes

Alluvial and Troublesome Aquifers

Reference Date	(Apodaca & Bails, 1999)	USGS WRIR-98-4255 1999	USGS WRIR-98-4255 1999	USGS WRIR-98-4255 1999
Drainage Basin(s)		Entire Fraser Valley	Entire Fraser Valley	Entire Fraser Valley
Aquifer Investigated		Alluvial Only	U Troublesome Only	Both
Type of Reservoir		Unconfined	Unconfined	Unconfined
Exent of Troublesome Aquifers (sq mi)		22.0	52.0	52.0
Exent of Troublesome Aquifers (ac)		14,080	33,280	33,280
Number of Wells - Data Base				129
Well Density (wells per sq mi)				
Well Depths Included in Study				
Gross Thickness (Ref Drilling Depth-ft)				500
Depth to Static Water Level (Av-ft)				3-240
Depth to Static Water Level (Range)				
Thickness of Sat Sands (Av-ft)		52		
Range Thickness Sat Sands				
Thickness of Non Sand (Av-ft)				
Range Thickness Sat Sands				
Total Saturated Thickness (Av-ft)			378	400
Sat Thickness (Range)				
Transmissivity (gpd/ft)		12000	5000-11000	5000-11000
Hydraulic Conductivity (ft/day)				
Hydraulic Conductivity (cm/sec)				
Effective Water Bearing Zones (Av N/G)				
Effective Water Bearing Zones (Range)				
Specific Yield / effective porosity (Av%)		20%	12%	12.4%
Specific Yield / effective porosity (Range)				12%-20%
Volume of Sat Thickness (Av-ac-ft)		728,020	12,583,980	13,312,000
Volume of Sat Thickness (Range)				
Volume Available Water (Av-ac-ft)		145,604	1,510,078	1,655,682
Volume Available Water (Range)				1.6E6-2.7E6
Volume Den of Available Water (acft/sq mi)				

3b

Summary of Historical Study
Apodaca & Bails, 1999
USGS report wri-98-4255

Parameters Used for Fraser Valley
In-Place and Accessible
Water Volumes

Alluvial and Troublesome Aquifers

Volume and parameters annotated in
"bold red" have been derived from
quoted area, saturated thickness and
specific yields

In some cases, no parameter
breakdown between aquifers were
noted

Reference Date	(Bauch & Bails, 2004)	USGS WRIR-03-4275	USGS WRIR-03-4275	USGS WRIR-03-4275
		2004	2004	2004
Drainage Basin(s)	Entire Fraser Valley	Entire Fraser Valley	Entire Fraser Valley	
Aquifer Investigated	Alluvial Only	U Troublesome Only	Both	
Type of Reservoir	Unconfined	confined	Both	
Exent of Troublesome Aquifers (sq mi)	22.0	52.0	52.0	
Exent of Troublesome Aquifers (ac)	14,080	33,280	33,281	
Number of Wells - Data Base	291	162		
Well Density (wells per sq mi)	0.021	0.005		
Well Depths Included in Study	0-140	80-600	0-600	
Gross Thickness (Ref Drilling Depth-ft)	0-140	500		
Depth to Static Water Level (Av-ft)	9			
Depth to Static Water Level (Range)				
Thickness of Sat Sands (Av-ft)	52	55		
Range Thickness Sat Sands				
Thickness of Non Sand (Av-ft)				
Range Thickness Sat Sands				
Total Saturated Thickness (Av-ft)	52	55		
Sat Thickness (Range)				
Transmissivity (gpd/ft)	12000	5000		
Hydraulic Conductivity (ft/day)		12.2		
Hydraulic Conductivity (cm/sec)				
Effective Water Bearing Zones (Av N/G)		11%		
Effective Water Bearing Zones (Range)		2%-35%		
Specific Yield / effective porosity (Av%)	20%	20%	20%	
Specific Yield / effective porosity (Range)				
Volume of Sat Thickness (Av-ac-ft)	728,020	1,830,400	2,558,420	
Volume of Sat Thickness (Range)	7.14E5-7.65E5			
Volume Available Water (Av-ac-ft)	145,604	366,080	511,684	
Volume Available Water (Range)				
Volume Den of Available Water (acft/sq mi)				

3c

Summary of Historical Study
Bauch & Bails, 2004
USGS report wri-03-4275

Parameters Used for Fraser Valley
In-Place and Accessible
Water Volumes

Alluvial and Troublesome Aquifers

Volume and parameters annotated in
"bold red" have been derived from
quoted area, saturated thickness and
specific yields

In some cases, no parameter
breakdown between aquifers were
noted

Table A3-1a, A3-1b. Summary of legal water decrees issued within the Greater Pole Creek Basin. The decrees are the basis for the number of wells each development may drill, maximum annual production per well, depth and/or formation limitations, and the use (domestic, commercial, municipal or irrigation). These have served as a basis for estimating possible consumption parameters discussed in **Section 3.4** of this report. Complete documents can be obtained from the Colorado Division of Water Resources (see reference list).

1a Summary of Water Decrees – Residential Developments with Augmentation Plans

Developments Augmentation Plans	Decree	Filing Date	Max # Wells	Max Well Vol/Yr (ac-ft)	Max All Wells Vol/Yr	Max Well Prod Rate (gal/min)	Depth Limitation	Formation Limitation	Tributary Source	Purpose
Fairways at Pole Creek	81CW105	4/30/1981	1	95.00	95.0	80	None Specified	Troublesome	Non- Tributary (confined aquifer??)	Irrigation (Aug only)
Fairways at Pole Creek	96CW175	6/21/1996	263	0.35	92.1	15	None Specified	None Specified	Pole Creek / Fisher Creek	Residential
Fairways at Pole Creek	03CW185	8/28/2003	7	None Specified	None Specified	50	None Specified	None Specified	Pole Creek / Fisher Creek	Irrigation and Other
Young Life	93CW298	12/28/1993	5	43	215.0	30	<200 ft	Alluvium / Upper Troublesome Only *	Crooked Creek	Commercial
Stage Coach Meadows	99CW046	3/30/1999	60	0.346	20.8	15	None Specified	Fractured Granite / Upper Troublesome*	Crooked Creek	Residential
Sheep Mtn Ridge Estates	99CW147	7/30/1999	23	0.314	7.2	15	None Specified	None Specified	Skunk Creek	Residential

1b Summary of Water Decrees – Residential Developments with Augmentation Plans

Developments Augmentation Plans	Decree	Filing Date	Max # Wells	Max Well Vol/Yr (ac-ft)	Max All Wells Vol/Yr	Max Well Prod Rate (gal/min)	Depth Limitation	Formation Limitation	Tributary Source	Purpose
Pole Creek Timbers	99CW094	5/28/1999	40	0.333	13.3	15	None Specified	Troublesome	Crooked Creek	Residential
Pole Creek Meadows	94CW223	9/30/1994	103	0.36	37.1	15	<250 ft	Upper Troublesome Only*	non specified	Residential
Black Forest Estates	96CW246	9/30/1996	7	0.392	2.7	15	<200 ft	Upper Troublesome Only*	Pole Creek	Residential

* Deepening into Lower Troublesome requires notification and approval by SEO

Municipal / Commercial / Irrigation / Recreation

Tabernash Wtr & Sanitation District	01CW176	7/30/2001	1	161	161.0	100	>500 ft	Troublesome	Pole Creek Crooked Creek Thomas Creek	Residential Commercial Irrigation
YMCA of the Rockies	16CW3037 21CW3052	11/12/2017 3/10/2022	Surface Water	NA	104.4	100	NA	NA	Pole Creek Springs	Commercial - Irrigation- Recreation

Table A3-2a, A3-2b. Lithologic drilling log for TMWS #2 municipal well with interpreted aquifer intervals and complements well completion data (Fig 5.4) and geophysical logs (Fig 5.5).

2a		
Tabernash Water and Sanitation District Well - TMWS # 2 – Permit # 61836-F – Lith Drilling Log		
Depth Below GL (ft)	Sample Description	
0 - 12	Clay: sandy	Water Table @ 46 feet
12 - 35	Sand and gravel	
35 - 50	Clay	
50 - 75	Sandstone to Siltstone: tan chips that are easily broken, very fine grained to silt, trace medium grains, subrounded (SR), quartz – clear to colored, some black grains and fragments	Alluvial Aquifer
75 - 85	Sandstone: medium grained, lammish, quartz, micaceous, subangular (SA) to SR, trace siltstone, fair sorting	
85 - 90	Sandstone: as above, medium to coarse grained	
90 - 95	Sandstone: as above, medium grained, increase in mica (muscovite)	Upper Troublesome Aquifer
95 - 120	poor samples, increase in tan siltstone/sandstone chips, 110 – 115 ft. large brown chips that are very hard	
120 - 130	Sandstone: medium grained with some fine to medium gravel (granite), micaceous, fair to poor sorting, SR to SA	
130 - 145	Siltstone: tan, clayey in part	Upper Troublesome Aquifer
145 - 150	Clay: brown, sticky	
150 - 155	Clay: gray, soft, sticky	
155 - 160	Clay: reddish brown, soft, sticky	
160 - 165	Sand: medium grained, quartz and other minerals, gray clay matrix?	
165 - 175	Clay: reddish brown to gray downward, sandy in part, sticky in part, trace sandstone chips downward	
175 - 185	Sand: medium grained, pinkish, colored quartz, poor sorting, SA	Upper Troublesome Aquifer
185 - 200	Siltstone: tan, sandy - very fine grained, hard, gray clay matrix increasing downward	
200 - 215	Clay: reddish brown, soft, some siltstone chips	
215 - 220	no sample	Upper Troublesome Aquifer
220 - 245	Sandstone: medium grained, pinkish, colored quartz, poor sorting, SA to A	
245 - 250	Clay: gray, with sand as above, maybe clay matrix transition	
250 - 255	Clay: gray, soft, sticky	Upper Troublesome Aquifer
255 - 270	Sandstone: as above, very micaceous (muscovite), grayish color	
270 - 275	Very poor sample: sandy, brown	
275 - 300	Clay: tan, with sand increasing downward - fine to medium grained, quartz and black grains	Upper Troublesome Aquifer
300 - 320	Sandstone: medium to fine grained, grayish, quartz and dark grains, muscovite and biotite, SA, fair sorting	
320 - 325	Clay: tan, with sand as above	
325 - 425	Sandstone: as above, slightly clayey in part (maybe polymer)	Lower Troublesome Aquifer
425 - 430	Sandstone: as above, slightly coarser, no clay	
430 - 435	Sandstone: same as 325 to 425 ft.	
435 - 460	Clay (sample from bit): slightly reddish brown, semi-firm, pliable, some medium to coarse grained sand mixed in	Lower Troublesome Aquifer
460 - 495	Sandstone: fine grained, lammish, quartz, micaceous, trace colored grains, slightly clayey to silty, SA to SR	
495 - 518	Sandstone: as above, medium to fine grained, no clay	

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
yard (yd)	0.9144	meter (m)
Area		
acre	4,047	square meter (m ²)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm ²)
acre	0.004047	square kilometer (km ²)
square foot (ft ²)	929.0	square centimeter (cm ²)
square foot (ft ²)	0.09290	square meter (m ²)
square inch (in ²)	6.452	square centimeter (cm ²)
section (640 acres or 1 square mile)	259.0	square hectometer (hm ²)
square mile (mi ²)	259.0	hectare (ha)
square mile (mi ²)	2.590	square kilometer (km ²)
Volume		
barrel (bbl; petroleum, barrel=42 gal)	1 0.1590	cubic meter (m ³)

Multiply	By	To obtain
ounce, fluid (fl. Oz)	0.02957	liter (L)
pint (pt)	0.4732	liter (L)
quart (qt)	0.9464	liter (L)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m ³)
gallon (gal)	3.785	cubic decimeter (dm ³)
million gallons (Mgal)	3,785	cubic meter (m ³)
billion gallons (Ggal)	3,785	cubic kilometer (km ³)
cubic inch (in ³)	16.39	cubic centimeter (cm ³)
cubic inch (in ³)	0.01639	cubic decimeter (dm ³)
cubic inch (in ³)	0.01639	liter (L)
cubic foot (ft ³)	28.32	cubic decimeter (dm ³)
cubic foot (ft ³)	0.02832	cubic meter (m ³)
cubic yard (yd ³)	0.7646	cubic meter (m ³)
cubic mile (mi ³)	4.168	cubic kilometer (km ³)
acre-foot (acre-ft)	1,233	cubic meter (m ³)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm ³)
Flow rate		
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m ³ /s)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m ³ /yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm ³ /yr)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per minute (ft/min)	0.3048	meter per minute (m/min)
foot per hour (ft/h)	0.3048	meter per hour (m/h)
foot per day (ft/d)	0.3048	meter per day (m/d)

Multiply	By	To obtain
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
cubic foot per second per square mile ([ft ³ /s]/mi ²)	0.01093	cubic meter per second per square kilometer ([m ³ /s]/km ²)
cubic foot per day (ft ³ /d)	0.02832	cubic meter per day (m ³ /d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m ³ /d)
gallon per day per square mile ([gal/d]/mi ²)	0.001461	cubic meter per day per square kilometer ([m ³ /d]/km ²)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m ³ /s)
million gallons per day per square mile ([Mgal/d]/mi ²)	1,461	cubic meter per day per square kilometer ([m ³ /d]/km ²)
inch per hour (in/h)	0.0254	meter per hour (m/h)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
Mass		
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	metric ton (t)
ton, long (2,240 lb)	1.016	metric ton (t)
Pressure		
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)
inch of mercury at 60 °F (in Hg)	3.377	kilopascal (kPa)
pound-force per square inch (lbf/in ²)	6.895	kilopascal (kPa)
pound per square foot (lb/ft ²)	0.04788	kilopascal (kPa)

Multiply	By	To obtain
pound per square inch (lb/in ²)	6.895	kilopascal (kPa)
Density		
pound per cubic foot (lb/ft ³)	16.02	kilogram per cubic meter (kg/m ³)
pound per cubic foot (lb/ft ³)	0.01602	gram per cubic centimeter (g/cm ³)
Energy		
kilowatthour (kWh)	3,600,000	joule (J)
Radioactivity		
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)
Specific capacity		
gallon per minute per foot ([gal/min]/ft)	0.2070	liter per second per meter ([L/s]/m)
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)
Hydraulic gradient		
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
Transmissivity		
foot squared per day (ft ² /d)	0.09290	meter squared per day (m ² /d)
Application rate		
pound per acre per year ([lb/acre]/yr)	1.121	kilogram per hectare per year ([kg/ha]/yr)
Leakance		
foot per day per foot ([ft/d]/ft)	1	meter per day per meter ([m/d]/m)
inch per year per foot ([in/yr]/ft)	83.33	millimeter per year per meter ([mm/yr]/m)
International System of Units to U.S. customary units		

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
Area		
square meter (m ²)	0.000247 1	acre
hectare (ha)	2.471	acre
square hectometer (hm ²)	2.471	acre
square kilometer (km ²)	247.1	acre
square centimeter (cm ²)	0.001076	square foot (ft ²)
square meter (m ²)	10.76	square foot (ft ²)
square centimeter (cm ²)	0.1550	square inch (in ²)
square hectometer (hm ²)	0.003861	section (640 acres or 1 square mile)
hectare (ha)	0.003861	square mile (mi ²)
square kilometer (km ²)	0.3861	square mile (mi ²)
Volume		
cubic meter (m ³)	6.290	barrel (petroleum, 1 barrel = 42 gal)
liter (L)	33.81402	ounce, fluid (fl. Oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)

Multiply	By	To obtain
cubic meter (m ³)	264.2	gallon (gal)
cubic decimeter (dm ³)	0.2642	gallon (gal)
cubic meter (m ³)	0.000264 2	million gallons (Mgal)
cubic kilometer (km ³)	264.2	billion gallons (Ggal)
cubic centimeter (cm ³)	0.06102	cubic inch (in ³)
cubic decimeter (dm ³)	61.02	cubic inch (in ³)
liter (L)	61.02	cubic inch (in ³)
cubic decimeter (dm ³)	0.03531	cubic foot (ft ³)
cubic meter (m ³)	35.31	cubic foot (ft ³)
cubic meter (m ³)	1.308	cubic yard (yd ³)
cubic kilometer (km ³)	0.2399	cubic mile (mi ³)
cubic meter (m ³)	0.000810 7	acre-foot (acre-ft)
cubic hectometer (hm ³)	810.7	acre-foot (acre-ft)
Flow rate		
cubic meter per second (m ³ /s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per year (m ³ /yr)	0.000811	acre-foot per year (acre-ft/yr)
cubic hectometer per year (hm ³ /yr)	811.03	acre-foot per year (acre-ft/yr)
meter per second (m/s)	3.281	foot per second (ft/s)
meter per minute (m/min)	3.281	foot per minute (ft/min)
meter per hour (m/h)	3.281	foot per hour (ft/h)
meter per day (m/d)	3.281	foot per day (ft/d)
meter per year (m/yr)	3.281	foot per year ft/yr)
cubic meter per second (m ³ /s)	35.31	cubic foot per second (ft ³ /s)
cubic meter per second per square kilometer ([m ³ /s]/km ²)	91.49	cubic foot per second per square mile ([ft ³ /s]/mi ²)

Multiply	By	To obtain
cubic meter per day (m ³ /d)	35.31	cubic foot per day (ft ³ /d)
liter per second (L/s)	15.85	gallon per minute (gal/min)
cubic meter per day (m ³ /d)	264.2	gallon per day (gal/d)
cubic meter per day per square kilometer ([m ³ /d]/km ²)	684.28	gallon per day per square mile ([gal/d]/mi ²)
cubic meter per second (m ³ /s)	22.83	million gallons per day (Mgal/d)
cubic meter per day per square kilometer ([m ³ /d]/km ²)	0.000684 4	million gallons per day per square mile ([Mgal/d]/mi ²)
meter per hour (m/h)	39.37	inch per hour (in/h)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
kilometer per hour (km/h)	0.6214	mile per hour (mi/h)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
metric ton (t)	1.102	ton, short [2,000 lb]
metric ton (t)	0.9842	ton, long [2,240 lb]
Pressure		
kilopascal (kPa)	0.009869	atmosphere, standard (atm)
kilopascal (kPa)	0.01	bar
kilopascal (kPa)	0.2961	inch of mercury at 60°F (in Hg)
kilopascal (kPa)	0.1450	pound-force per inch (lbf/in)
kilopascal (kPa)	20.88	pound per square foot (lb/ft ²)
kilopascal (kPa)	0.1450	pound per square inch (lb/ft ²)
Density		
kilogram per cubic meter (kg/m ³)	0.06242	pound per cubic foot (lb/ft ³)
gram per cubic centimeter (g/cm ³)	62.4220	pound per cubic foot (lb/ft ³)

Multiply	By	To obtain
Energy		
joule (J)	0.000000 2	kilowatthour (kWh)
Radioactivity		
becquerel per liter (Bq/L)	27.027	picocurie per liter (pCi/L)
Specific capacity		
liter per second per meter ([L/s]/m)	4.831	gallon per minute per foot ([gal/min]/ft)
Hydraulic conductivity		
meter per day (m/d)	3.281	foot per day (ft/d)
Hydraulic gradient		
meter per kilometer (m/km)	5.27983	foot per mile (ft/mi)
Transmissivity		
meter squared per day (m ² /d)	10.76	foot squared per day (ft ² /d)
Application rate		
kilogram per hectare per year ([kg/ha]/yr)	0.8921	pound per acre per year ([lb/acre]/yr)
Leakance		
meter per day per meter ([m/d]/m)	1	foot per day per foot ([ft/d]/ft)
millimeter per year per meter ([mm/yr]/m)	0.012	inch per year per foot ([in/yr]/ft)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8.$$

Datums

Vertical coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Horizontal coordinate information is referenced to the World Geodetic System 1984 (WGS 84).

Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius ($\mu\text{S}/\text{cm}$ at 25 °C).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

NAD 83 North American Datum of 1983

WGS 84 World Geodetic System Datum of 1988

USGS U.S. Geological Survey