Hydrogeologic Characterization of Dutch Canyon, Scappoose, Oregon

by

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requirements for the degree of

Master of Science
in
Geology

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Abstract

Dutch Canyon is located directly west of the City of Scappoose in Columbia County Oregon. This area is proximate to Highway 30, a major access corridor to downtown Portland, and is experiencing a population increase, which is expected to continue and likely accelerate. As a result, there is growing pressure on water resources. Individual and community efforts to utilize groundwater resources have been hampered by generally poor groundwater yields and water quality concerns outside of the Columbia River corridor and a lack of published hydrogeologic information for the region.

The intent of this study is to identify the water-bearing units present in Dutch Canyon and to characterize water quality within these units. The physical hydrogeology of Dutch Canyon was assessed mainly through the collation of 196 local well reports that contained lithologic information from which individual hydrostratigraphic units were identified and characterized. Hydraulic parameters for individual units were estimated using pump rates and drawdowns provided in select well reports. Water quality for the units identified was assessed through the collection of 48 samples of well, spring, and stream water from Dutch Canyon. Measurements of pH, specific conductivity, temperature, dissolved oxygen, reduction potential, and alkalinity were recorded in the field and samples were analyzed for major ions, arsenic, and stable isotopes.

The major water-bearing units of Dutch Canyon were separated into five physically distinct hydrostratigrapic units: the lower, middle, and upper units of the sedimentary Lower Miocene Scappoose Formation, and the Wapshilla Ridge and Ortley members of the Lower to Middle Miocene Grande Ronde Basalt. Groundwater flow likely occurs in discrete, relatively thin (~2- to 10-m thick) zones within the Grand Ronde Basalt members. These units only occur along the slopes and ridges of Dutch Canyon west of the Portland Hills Fault, which parallels the eastern margin of the study area. The Scappoose Formation units contain clay- and silt-rich layers and lenses that limit the useable aquifer volume and vertical movement of groundwaters. In general, all hydrostratrigraphic units east of the Portland Hills Fault have low transmissivities and water wells completed in each of them are commonly low- yielding wells, though there are some exceptions.

Geochemically, the lower and middle units of the Scappoose Formation were similar to one another with many wells yielding groundwater with high total dissolved solids (TDS) contents (mean TDS = 330 mg L^{-1}; n = 27). Nearly 20% of the wells sampled that were screened in these units (5 of 27) yielded groundwater that exceeded the U.S. Environmental Protection Agency's National Secondary (non-enforceable) Drinking Water Regulation standard of 500 mg L^{-1} TDS. The upper unit of the Scappoose Formation and the overlying Grande Ronde Basalt members generally yield water with lower TDS contents (mean < 200 mg L^{-1}; maximum = 342 mg L^{-1}; n = 20). Groundwater resources in Dutch Canyon are limited and low well yields are common. The primary water quality concern is saline water, which is generally found in the lower and middle units of the Scappoose Formation near the valley floor. Low recharge rates determined from hydrograph analysis of stream discharge measurements are consistent with the geology and steep terrain of the area and further limit the available groundwater and the degree of flushing of what may be connate waters in the deeper units.

Acknowledgments

I would like to begin by thanking my thesis committee; Ben Perkins, Michael Cummings, and Ken Lite. Your assistance and guidance is appreciated. I would like to especially thank Ben who has greatly improved my critical thinking and analysis skills as well as my understanding of groundwater chemistry. He has been extremely patient and understanding throughout this project and has provided excellent guidance. Thank you, Ben.

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Next, I would like to thank the property owners in Dutch Canyon who allowed me to sample waters from their personal wells. In almost every case, they were welcoming and often provided me with useful information about their groundwater and neighbors who would be willing to allow me to sample from their wells.

I would like to thank friends and family who were always supportive of me during this project and encouraged me to keep working. My mother, Mary Chris, and father, David, have helped me to remain focused and motivated me to always do better. My mother-in-law Carol and my late father-in-law Jim have been especially helpful during this process and their support will never be forgotten.

Mostly, I would like to thank my wife Lynn Ann, and my sons, Dylan and Hutton, for their unwavering love and support. They have provided me with motivation when it has most been needed. It has not always been easy working from home with a young child but Lynn Ann has provided me with more help than I could ask for.

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CHAPTER 1. INTRODUCTION AND BACKGROUND

Purpose and Scope

The northern Oregon Coast Range is a complex geological landscape comprised of middle Tertiary marine sedimentary and basalt units overlain by late Tertiary Columbia River Basalt Group (CRBG) units, often mantled by loess, that have been displaced by frequent landslides and faulting (Niem and Niem, 2002). Despite average precipitation over 100 cm, water resources in the region are constrained by the rugged topography, via increased runoff in areas steep slopes, and limited surface water impoundments. Individual and community efforts to utilize groundwater resources have been hampered by generally poor groundwater yields and water quality concerns outside of the Columbia River corridor and a lack of published hydrogeologic information for the region. The area is experiencing a population increase (Census.gov, 2010), especially proximate to major access corridors such as Highway 30 and the Scappoose-Vernonia Highway, which is expected to continue and likely accelerate. The resulting increasing demand for water resources requires a better understanding of regional and local hydrogeology.

Geography of Study Area

The study area is located primarily in Columbia County, which is located in northwest Oregon, directly north of Washington County, northwest of Multnomah County, and east of Clatsop County (Figs. 1.1 and 1.2). Columbia County’s landscape is largely defined by the Tualatin Mountains and Coast Range Mountains. The eastern portion of the county borders the Columbia River, Multnomah Channel, and the Portland Basin, a roughly 2000 square kilometer structural and topographic basin (Beeson et al., 1989).

Columbia County had maintained a stable population, but has seen growth in recent decades, from 36,000 in 1980 to 44,000 in 2000, to a population of 49,351 in 2010 (Census.gov, 2010). It is estimated that the majority of the new residents are people who work in nearby Portland. The first sizeable city from Portland within Columbia County is Scappoose, located 30 km northwest of downtown Portland along Highway 30. Scappoose's 2010 population of 6,862 is a 38% increase from its 2000 population of 4,976 (Census.gov, 2010). The county foresees continued rapid growth, similar to that experienced by the city of Hillsboro, Oregon, also populated by many people working in Portland who sought to live outside the large city, and whose population has jumped by 250% since 1980 (Census.gov, 2010b).

The majority of the population of Scappoose resides in the flat floodplain of the Columbia River, near Highway 30. Most residents use city water that is sourced from both an above ground reservoir in the upper drainage of South Fork Scappoose Creek, located west of Scappoose and from wells constructed to alluvial aquifers along the Columbia River. Dutch Canyon, located due west of Scappoose, has room to accommodate population growth around and within the wide floodplain along the lower reaches of South Fork Scappoose Creek.

Geologic Framework

1.1.1 Regional Setting

Dutch Canyon is a river valley carved by the South Fork Scappoose Creek, located within the northwest-trending Tualatin Mountains, a late Cenozoic anticline that is faulted on its northeast limb by the Portland Hills Fault Zone (Beeson et al., 1976; Beeson et al., 1985). The Tualatin Mountains separate the Portland Basin to the northeast from the Tualatin Basin to the southwest (Fig. 1.1).

The topography of Dutch Canyon is characterized by a central river valley with low relief, with a flood plain between 200-400 meters wide and rugged valley flanks to the north and south. Elevations in the area vary from 20 m above mean sea level (amsl) along the eastern floor to 420 m amsl on the northern canyon ridge. The flanks of the valley vary in gradient from 0.05 to 0.15 locally. Feeder streams form dendritic drainage patterns toward the South Fork Scappoose Creek, which flows from west to east. The Creek and main valley floor have a gradient of 0.01 towards the east, dropping 50 m in 4 km.

Much of the area along the southern valley side displays hummocky topography (Fig. 1.2), indicative of landslide deposits. This area has been identified as a major landslide complex (Madin and Niewendorp, 2008). A prominent scarp can also be seen in the digital elevation model (DEM) and orthoimagery like LiDAR. The Portland Hills Fault Zone is present along the eastern boundary of Dutch Canyon, between the valley and Highway 30. Two smaller faults have also been identified within 2 km west of the

Portland Hills Fault and less than 5 km south of Dutch Canyon (Madin and Niewendorp, 2008).

The local geology in Columbia County, Oregon is comprised of middle Miocene Columbia River Basalt Group (CRBG) basalt flows from the Grande Ronde Basalt overlying the sedimentary rocks of the middle Miocene Scappoose Formation (Fig. 1.3). Directly west of the main city of Scappoose is an area that provides a natural window through the CRBG into the stratigraphically lower marine units exposed at lower elevations.

In much of the northern Coast Range, the marine rocks underlying the CRBG are considered the hydrologic basement, but in Dutch Canyon they are targeted for groundwater extraction due to their surface exposure. Numerous water well installations, many recent and resulting from increased residential development in the Canyon, provide the needed spatial concentration of subsurface data to characterize hydrostratigraphic relationships and the opportunity to sample and analyze waters from various units.

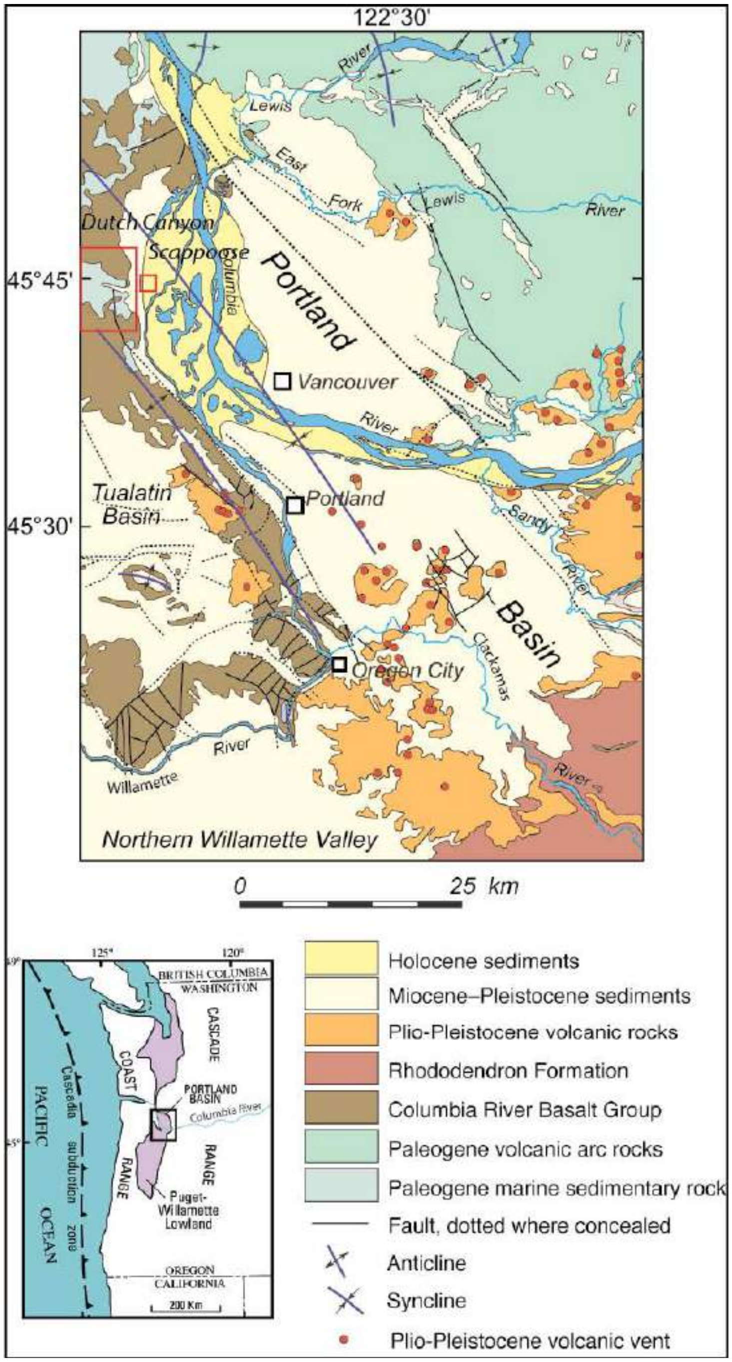


Figure 1.1. Generalized geology of Portland Basin and vicinity, modified from Evarts et al. (2009) and Blakely et al. (2000). Scappoose and Dutch Canyon are highlighted in red. Inset shows location of Portland Basin in forearc trough between Coast Range forearc high and Cascade Range volcanic arc.

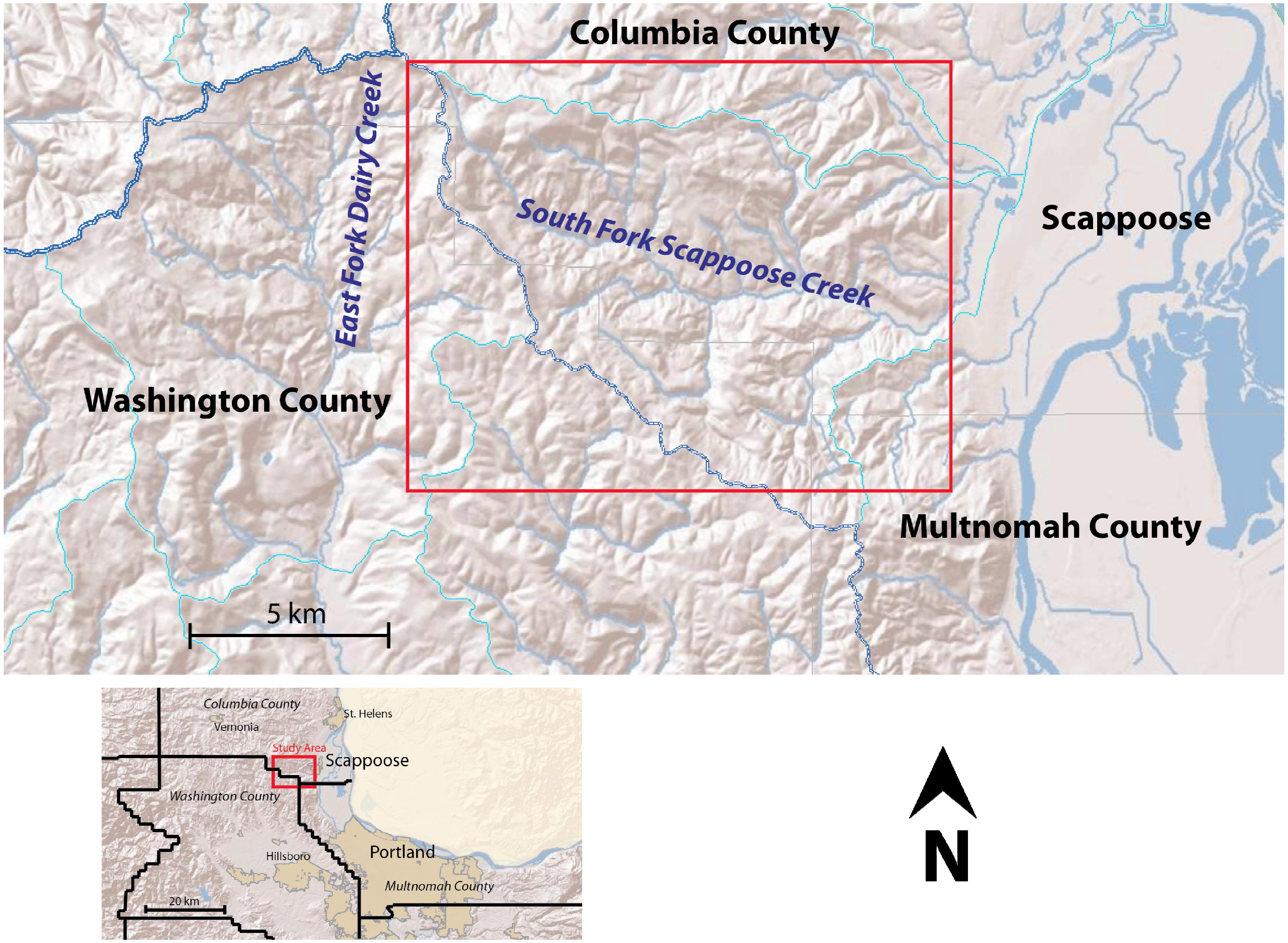


Figure 1.2. Digital Elevation Model (DEM) of Dutch Canyon. The river valley of the South Fork Scappoose Creek is visible in the middle of the canyon, flanked by steep canyon walls characterized by landslide topography (scarps and hummocks) to the south

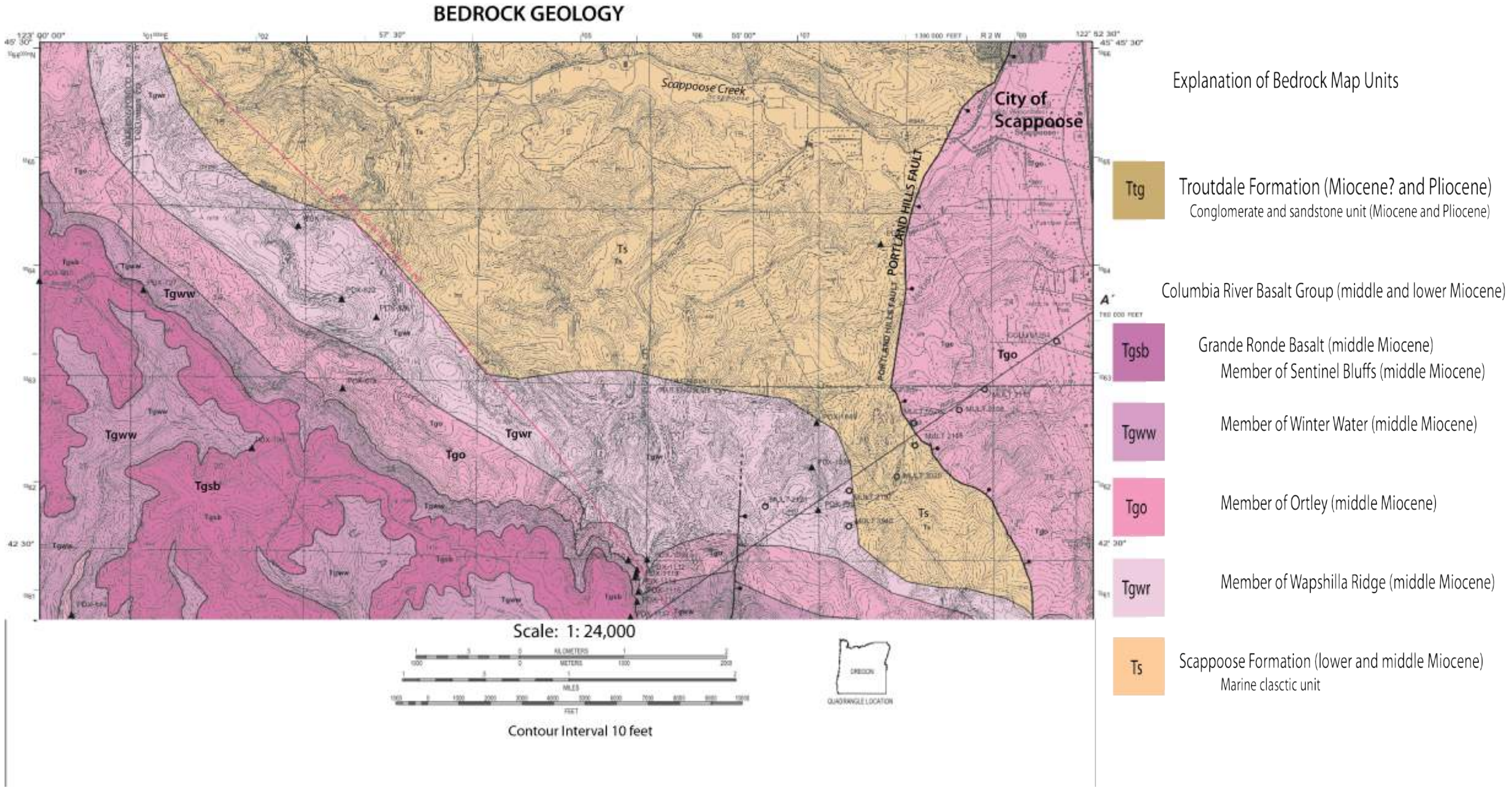


Figure 1.3. Detailed bedrock geology map of Scappoose and the southern half of Dutch Canyon, modified from Madin and Niewendorp (2008). The N-S Portland Hills Fault juxtaposes the younger Ortley member of the Grande Ronde Basalt with the older Scappoose Formation.

1.1.2 Geologic units of the study area

1.3.2.1 Scappoose Formation

The stratigraphy of the marine sedimentary units in Columbia County and surrounding areas in northwestern Oregon was initially described by Warren et al. (1945) who identified tuffaceous sandstones and mudstones in a sedimentary unit that contained a molluscan fauna bed above the Pittsburg Bluff Formation. Warren and Norbisrath (1946) named this formation the Scappoose Formation and described the unit as an Oligocene to early Miocene tuffaceous sandstone with shale beds that were capped by basalts that have since been defined as the CRBG. A type locality was not given but the best exposure of the Scappoose Formation was cited as along the South Fork of Scappoose Creek, which is located within Dutch Canyon.

The Scappoose Formation disconformably overlies the Oligocene Pittsburg Bluff Formation, a sedimentary unit comprised of fine-grained lithic-rich arkosic sandstone and buff colored silty sandstone. The Pittsburg Bluff Formation is lithologically similar to the Scappoose Formation, with the two units initially described as only being distinguished by their respective paleoflora and fauna (Warren and Norbisrath, 1946). Directly overlying the Scappoose Formation is the Wapshilla Ridge Member of the Grande Ronde Basalt that was deposited coeval with the upper Scappoose, as evidenced by an interfingering contact between the two units that may be observed in some locations (Ketrenos, 1986).

The thickness of the Scappoose Formation is typically between 150 and 250 meters (Van Atta and Kelty, 1985). The thickest it has been estimated to be is 457 meters thick near Buxton, Oregon (Warren and Norbisrath, 1946). The nearest stratigraphic thickness measurement to Dutch Canyon was 15 km to the northeast where it was determined to be 200 m thick. A series of stratigraphic columns for the Scappoose Formation were constructed by Ketrenos (1986) for central to northwestern Columbia County (Fig. 1.4).

Prior to the work of Warren and Norbisrath (1946), the Scappoose Formation was correlated with the Sooke Formation of Vancouver Island, B.C. (Clark and Arnold, 1923). It was also considered equivalent to the Nye mudstone and Yaquina Formation from the central Oregon coast and the Blakely Formation in southwest Washington (Snavely, 1963). Cressey (1973) also suggested that the Oswald West Mudstone in the Astoria Formation was a prodelta deep-water sequence of the Scappoose Formation. Using detailed petrographic techniques that had not yet been applied to the formation, Van Atta (1971) was able to delineate mineralogical differences in the lithology of the Scappoose and Pittsburg Bluff Formations. He found the sandstone of the Scappoose Formation to contain more quartz and less silt than the Pittsburg Bluff rocks.

The base of the Scappoose Formation, overlying the Pittsburg Bluff Formation, is a conglomerate with a thickness of 5-10 m. Warren and Norbisrath (1946) described the bottom of Scappoose Formation as cobble to boulder conglomerate with basalt clasts. Van Atta and Kelty (1985) described the unit in greater detail and determined the basalt clasts in the base of the Scappoose had the same major, minor, and trace element geochemistry as the mid-Miocene flows of the CRBG. This led Van Atta and Kelty (1985) to conclude the deposition of the Scappoose Formation was coeval with the eruption of the CRBG flows and to revise the age of the unit to mid-Miocene.

Ketrenos (1986) described the Scappoose Formation as often yellowish and gray with micaceous, lithic, quartzose, and arkosic sandstone compositions, often interbedded with mudstone and pebbles. She also divided the formation into five different groups, a framework supported basalt and mudstone conglomerate at the base, overlain by a well-sorted basalt conglomerate, followed by a dark gray, fine-grained sand unit, then a very fine-grained arkosic sand, and topped by a poorly sorted and loosely consolidated arkosic sand in contact and interbedded with the lower CRBG rocks (Fig. 1.5).

Petrographic analysis of interbeds within the Scappoose Formation by Eriksson (2002) revealed many lithic grains that were altered to clay with a smectite rim cement. Hand samples of this unit, from the middle portion of the Scappoose Formation, were described as being bluish-gray.

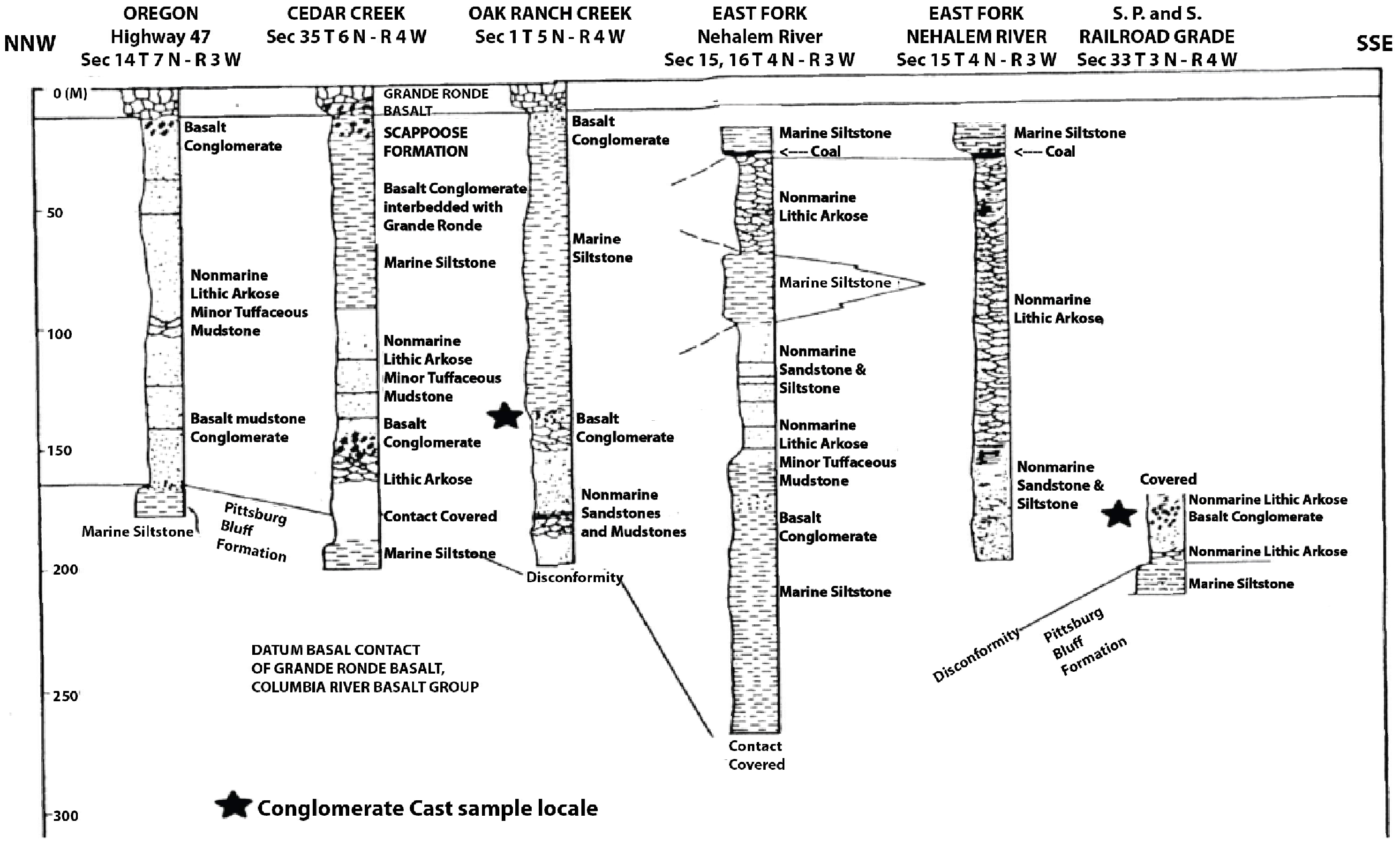
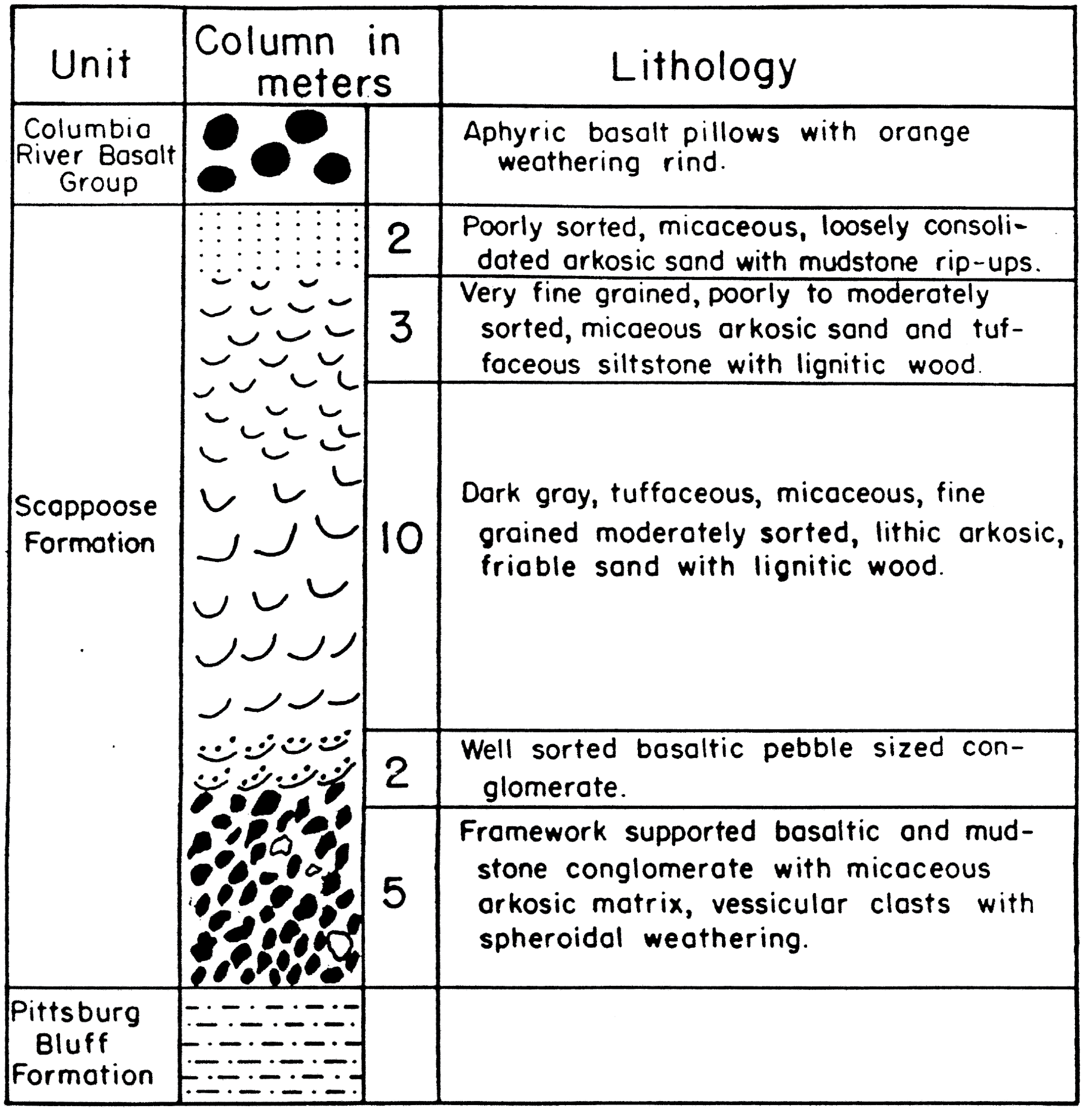


Figure 1.4. Stratigraphic Section of Scappoose Formation in central Columbia County (Ketrenos, 1986). Sections display lateral variation in lithologic thickness of marine and non-marine sediments

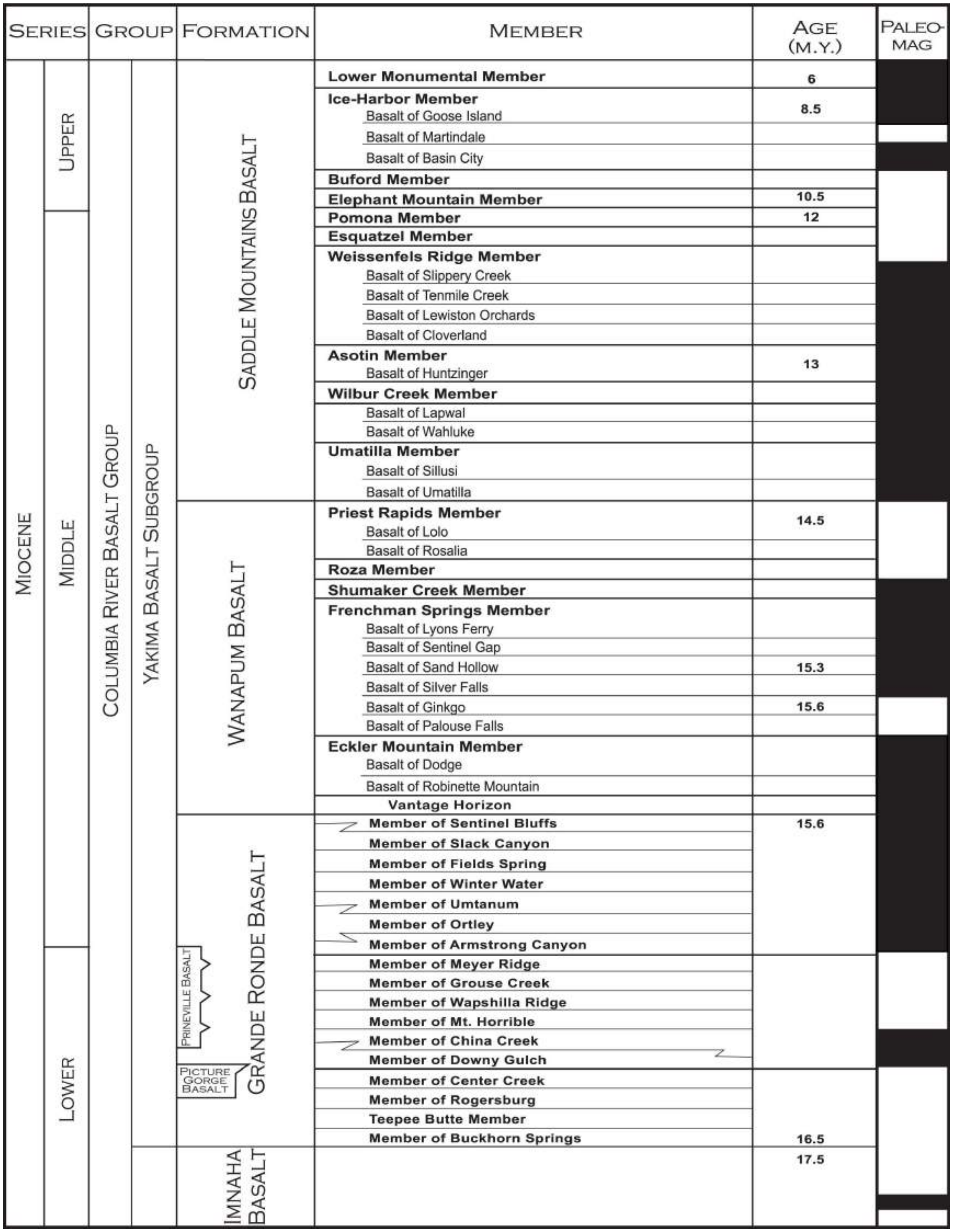


Unit	Column in meters		Lithology
Columbia River Basalt Group			Aphyric basalt pillows with orange weathering rind.
Scappoose Formation		2	Poorly sorted, micaceous, loosely consolidated arkosic sand with mudstone rip-ups.
		3	Very fine grained, poorly to moderately sorted, micaeous arkosic sand and tuffaceous siltstone with lignitic wood.
		10	Dark gray, tuffaceous, micaceous, fine grained moderately sorted, lithic arkosic, friable sand with lignitic wood.
		2	Well sorted basaltic pebble sized conglomerate.
		5	Framework supported basaltic and mudstone conglomerate with micaceous arkosic matrix, vessicular clasts with spheroidal weathering.
Pittsburg Bluff Formation			

Figure 1.5. Generalized stratigraphic column of Scappoose Formation with detailed lithologic information (Ketrenos, 1986).

1.3.2.2 Grande Ronde Basalt Formation

Above the Scappoose Formation lies the middle Miocene Grande Ronde Basalt, part of the CRBG (Swanson et al., 1979). The CRBG is a series of Miocene to Pliocene tholeiitic basalt flows that erupted from fissures in eastern Oregon, Washington, and western Idaho. The basalt flows covered an area of 164,000 km^2 extending from the source area to the Willamette Valley and the northern Oregon coast. The total volume of the CRBG has been estimated at 173,000 km^3 (Tolan et al., 1989). Thicknesses of individual CRBG flows are typically less than 200 m. The stratigraphy of the CRBG (Fig. 1.6) has been delineated using geochemistry, paleomagnetics, and lithologic characteristics. The CRBG has been divided into five formations, the Imnaha, Picture Gorge, Grande Ronde, Wanapum, and Saddle Mountain. Each of these formations has been further subdivided into distinct units, members, and flows (Beeson et al., 1989). The Imnaha and Picture Gorge Formations are present only in central and eastern Oregon, having erupted into basins that remained topographically separate from the Columbia Plateau. The Grande Ronde Basalt is comprised of seventeen basalt units erupted between 17 to 15 Ma. It is the most extensive and voluminous formation of the CRBG with individual flows ranging in volume up to 3,000 km^3 (Tolan et al., 1989).



Series		Group		Formation	Member	Age (M.Y.)	Paleo-mag
Miocene	Upper	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	**Lower Monumental Member**	6	■
					Ice-Harbor Member Basalt of Goose Island	8.5	■
					Basalt of Martindale		□
					Basalt of Basin City		■
					Buford Member		□
					Elephant Mountain Member	10.5	□
	Middle				**Pomona Member**	12	□
					Esquatzel Member		□
					Weissenfels Ridge Member Basalt of Slippery Creek		■
					Basalt of Tenmile Creek		■
					Basalt of Lewiston Orchards		■
					Basalt of Cloverland		■
					Asotin Member Basalt of Huntzinger	13	■
					Wilbur Creek Member		■
					Basalt of Lapwal		■
					Basalt of Wahluke		■
					Umatilla Member Basalt of Sillusi		■
					Basalt of Umatilla		■
				Wanapum Basalt	**Priest Rapids Member** Basalt of Lolo	14.5	□
					Basalt of Rosalia		□
					Roza Member		□
					Shumaker Creek Member		■
					Frenchman Springs Member Basalt of Lyons Ferry		■
					Basalt of Sentinel Gap		■
					Basalt of Sand Hollow	15.3	■
					Basalt of Silver Falls		■
					Basalt of Ginkgo	15.6	□
					Basalt of Palouse Falls		□
					Eckler Mountain Member Basalt of Dodge		■
					Basalt of Robinette Mountain		■
					Vantage Horizon		■
				Grande Ronde Basalt	**Member of Sentinel Bluffs**	15.6	■
					Member of Slack Canyon		■
					Member of Fields Spring		■
					Member of Winter Water		■
					Member of Umtanum		■
					Member of Ortley		■
					Member of Armstrong Canyon		■
	Lower			Prineville Basalt	**Member of Meyer Ridge**		□
					Member of Grouse Creek		□
					Member of Wapshilla Ridge		□
					Member of Mt. Horrible		□
					Member of China Creek		■
					Member of Downy Gulch		■
				Picture Gorge Basalt	**Member of Center Creek**		□
					Member of Rogersburg		□
					Teepee Butte Member		□
					Member of Buckhorn Springs	16.5	□
				Imnaha Basalt		17.5	□ ■ □

Figure 1.6. Stratigraphic column of the Columbia River Basalt. Paleomagnetic data in the right column: black areas indicate a time of normal polarity while white areas indicate a time of reverse polarity. Modified from Reidel, 2003

In the northern Tualatin Mountains, five of the seventeen members of the Grande Ronde Basalt have been identified and mapped: Wapshilla Ridge, Ortley-Grouse Creek (undifferentiated, but locally referred to as Ortley), Umtanum, Winter Water, and Sentinel Bluffs. These members, excluding the Umtanum, have been identified in the Dutch Canyon area by Madin and Niewendorp (2008) via geochemical analysis of outcrop samples. The stratigraphically lowest of these units, the Wapshilla Ridge basalt, is the most voluminous of the Grande Ronde Basalts, although it varies in thickness locally due to deposition on and infilling of pre-existing topography. Large-scale flame structures provide evidence that the Wapshilla Ridge basalt was deposited over soft sediments comprising the upper Scappoose Formation. It can be distinguished by its reverse polarity and lithologic characteristics, such as extremely fine-grained groundmass, high glass content, and a highly developed microphyric texture (Broderson, 1995). Fresh exposures of the Wapshilla Ridge display plagioclase laths typically 1-2 mm long and 0.5 mm thick. This texture is difficult to distinguish in highly weathered zones where oxidation and basalt alteration zones are present. Geochemically, the Wapshilla Ridge has lower SiO_2 content and higher TiO_2 than the Ortley with concentrations of vanadium, barium, rubidium, zinc, and cesium inversely correlated with concentrations of lanthanum (Broderson, 1995).

Overlying the Wapshilla Ridge member is the Ortley member, which is also referred to as the Grouse Creek member (Eriksson, 2002). The Ortley member has been described as having a fine-grained groundmass, often low amounts of glass, and poorly developed microphyric texture with sparse amounts of 2-3 mm plagioclase laths and moderate amounts of 1 mm plagioclase laths. In many cases, the surface is a weathered green or blue (Broderson, 1995). The Ortley has been described as having up to six distinct flows in northwestern Columbia County (Eriksson, 2002).

In the study area, the Winter Water Member overlies the Ortley. The Winter Water member is described as being medium light-gray where fresh, with a fine-grained texture containing minor amounts of glass and 1-2 mm embayed plagioclase feldspar phenocrysts (Broderson, 1995).

The uppermost unit of the Grande Ronde in the study area is the Sentinel Bluffs member. The Sentinel Bluffs member is comprised of two main flows: 1) a medium dark gray unit with coarse- to fine-grained, 2-4 mm plagioclase feldspar phenocrysts in the lower flow, and 2) an aphyric upper flow.

1.1.3 Geologic Structures

The primary structure in Dutch Canyon is the Portland Hills Fault Zone, which has a northwest-striking, sinuous fault trace in the area northwest of Portland, Oregon (Madin, 2008). The structural relief of the Portland Hills Fault in Scappoose is ~250 meters, with several smaller faults displaying offset in the 10s of meters (Madin and Niewendorp, 2008). Previous work has shown the Portland Hills Fault Zone to display features of thrust and strike-slip faults with steeply dipping thrust faults most prominent in Portland (Blakely et al., 2004). Several micro earthquakes occurred along the fault in 1991, suggesting it is still seismically active. Much of the trace of the Portland Hills Fault is covered by massive landslide complexes and Missoula Flood deposits (Madin and Burns, 2007). The Portland Hills Fault Zone comprises part of the larger Portland

Hills-Clackamas River structural zone (Blakely, 1995), which has experienced folding as well as normal, thrust, and dextral strike-slip faulting since the middle Miocene (Beeson et al. 1985). This zone is one of several in northwestern Oregon that accommodate north-south shortening and clockwise rotation of the Oregon Coast Range (Beeson et al., 1985; Wells et al., 1998; Blakely et al., 2000).

CHAPTER 2. PHYSICAL HYDROGEOLOGY

2.1 Introduction

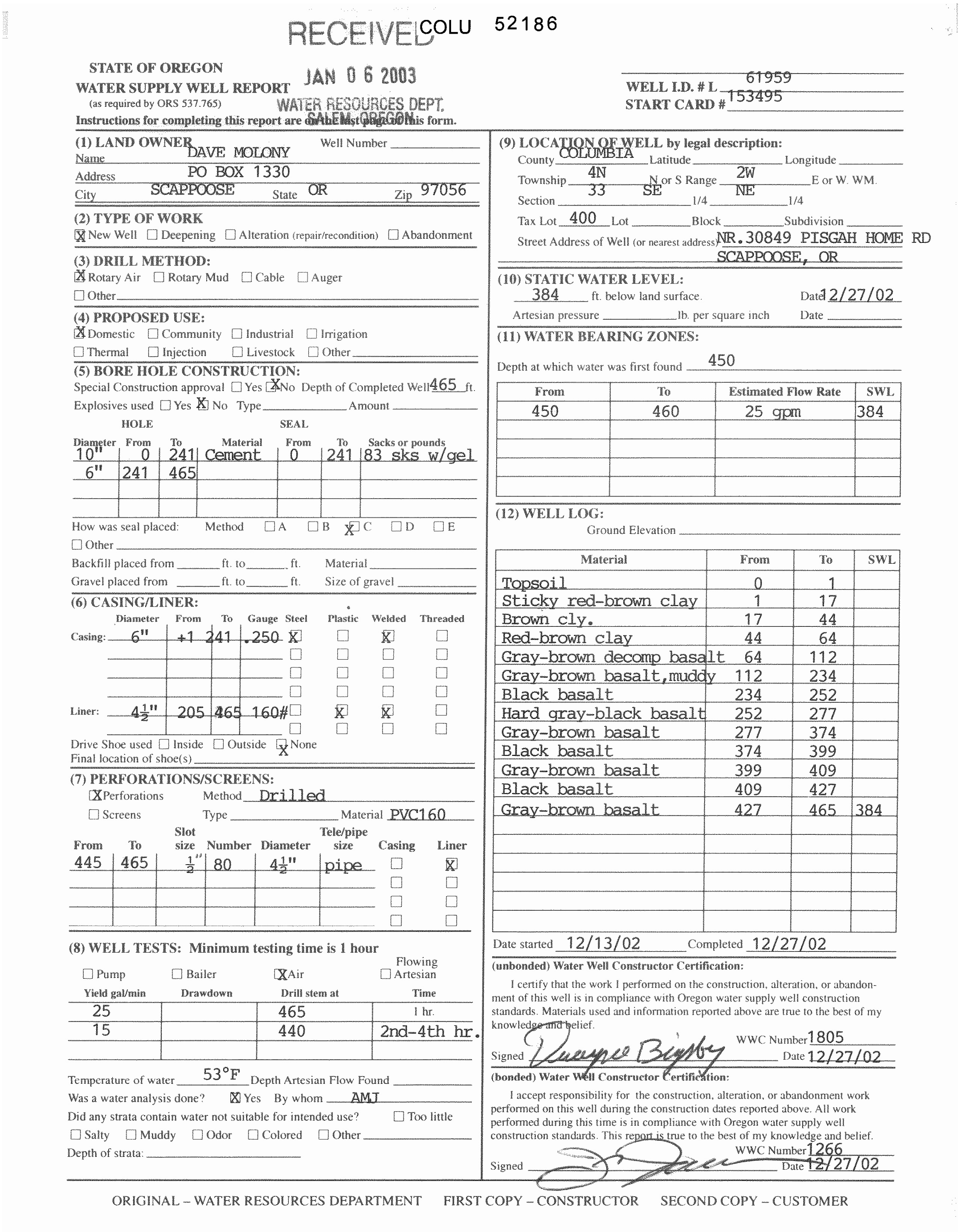
The physical hydrogeology in Dutch Canyon area has, to date, gone mostly unstudied. Although the physical geology of the Scappoose Formation was studied and described by Ketrenos (1986) and Van Atta and Kelty (1985), they did not discuss hydrogeologic characteristics. Much more is understood about the hydrogeology of the Grande Ronde Basalt units, which are productive aquifers throughout the region. Beeson et al. (1985) described limited vertical conductivity with primary water-bearing zones in the vesicular flow tops and pillowed and hyaloclastite flow bottoms. Groundwater recharge of CRBG aquifers occurs through exposed flowtops, fault zones, along unit contacts, and by vertical migration, which is often limited (Reidel, 2003). Basalt flowtops are highly permeable and infiltration rates will be higher where the flowtop is exposed than where a basalt flow interior is exposed. In order to properly understand the physical hydrogeology of the Dutch Canyon area, any and all descriptions of the subsurface geology with groundwater information needed to be located. As no comprehensive study of the local hydrogeology has occurred, the best option to compile geologic and groundwater data was via well reports filed for properties in Dutch Canyon.

2.2 Methods

2.2.1 Well Inventory

Much of Dutch Canyon is covered in thick vegetation and the area is mostly owned by private individuals, leaving minimal access to outcrops of sufficient quality to identify or sample. Thus, without drilling new boreholes, at great expense, to identify hydrostratigraphic units, the only existing windows into the subsurface are Oregon Department of Water Resources (OWRD) water well reports or "well logs." Well reports are required to be filed by water well drillers for each well completed and contain fields for the drillers to fill in information about the land owner, location, type of well, drilling method, construction details, type of casing or liner used, location and type of perforations or screens used, well testing, static water level, water-bearing zones, and lithologies encountered in the well (Fig. 2.1). From careful examination of this information, water-bearing zones can be identified, water level elevations can be determined, and specific capacities and, in some cases, transmissivities can be estimated for wells that were tested following installation.

A thorough search of the OWRD records located 196 logs for wells in the study area, with the deepest well extending 400 meters below the land surface. However, many well logs provide poor location information, poor descriptions of the bedrock and unconsolidated sediment they encounter, and or little information regarding hydraulic testing or water levels, while other logs provide a considerable level of detail. The reliability of the well logs was ascertained as described in the following sections and individual well logs either rejected or information used from them weighted accordingly to minimize the effects of incorrect lithologic or location information on the overall geologic model of the area. Of the 196 individual logs located, a total of 73 were utilized for the stratigraphic modeling but 181 provided at least some basic information regarding lithology and well yield in their area.



RECEIVED COLU 52186

JAN 0 6 2003
WATER RESOURCES DEPT.
SALEM, OREGON

STATE OF OREGON
WATER SUPPLY WELL REPORT
(as required by ORS 537.765)
Instructions for completing this report are on the last page of this form.

WELL I.D. # L 61959
START CARD # 153495

(1) LAND OWNER Well Number
Name DAVE MOLONY
Address PO BOX 1330
City SCAPPOOSE State OR Zip 97056

(2) TYPE OF WORK
☒ New Well ☐ Deepening ☐ Alteration (repair/recondition) ☐ Abandonment

(3) DRILL METHOD:
☒ Rotary Air ☐ Rotary Mud ☐ Cable ☐ Auger
☐ Other

(4) PROPOSED USE:
☒ Domestic ☐ Community ☐ Industrial ☐ Irrigation
☐ Thermal ☐ Injection ☐ Livestock ☐ Other

(5) BORE HOLE CONSTRUCTION:
Special Construction approval ☐ Yes ☒ No Depth of Completed Well 465 ft.
Explosives used ☐ Yes ☒ No Type Amount

HOLE			SEAL			
Diameter	From	To	Material	From	To	Sacks or pounds
10"	0	241	Cement	0	241	83 sks w/gel
6"	241	465				

How was seal placed: Method ☐ A ☐ B ☒ C ☐ D ☐ E
☐ Other
Backfill placed from ft. to ft. Material
Gravel placed from ft. to ft. Size of gravel

(6) CASING/LINER:

	Diameter	From	To	Gauge	Steel	Plastic	Welded	Threaded
Casing:	6"	+1	241	.250	☒	☐	☒	☐
					☐	☐	☐	☐
					☐	☐	☐	☐
					☐	☐	☐	☐
Liner:	$4\frac{1}{2}$"	205	465	160#	☐	☒	☒	☐
					☐	☐	☐	☐

Drive Shoe used ☐ Inside ☐ Outside ☒ None
Final location of shoe(s)

(7) PERFORATIONS/SCREENS:
☒ Perforations Method Drilled
☐ Screens Type Material PVC160

From	To	Slot size	Number	Diameter	Tele/pipe size	Casing	Liner
445	465	$\frac{1}{2}$"	80	$4\frac{1}{2}$"	pipe	☐	☒
						☐	☐
						☐	☐
						☐	☐

(8) WELL TESTS: Minimum testing time is 1 hour
☐ Pump ☐ Bailer ☒ Air ☐ Flowing Artesian

Yield gal/min	Drawdown	Drill stem at	Time
25		465	1 hr.
15		440	2nd-4th hr.

Temperature of water 53°F Depth Artesian Flow Found
Was a water analysis done? ☒ Yes By whom AMJ
Did any strata contain water not suitable for intended use? ☐ Too little
☐ Salty ☐ Muddy ☐ Odor ☐ Colored ☐ Other
Depth of strata:

(9) LOCATION OF WELL by legal description:
County COLUMBIA Latitude Longitude
Township 4N N or S Range 2W E or W. WM.
Section 33 SE 1/4 NE 1/4
Tax Lot 400 Lot Block Subdivision
Street Address of Well (or nearest address) NR.30849 PISGAH HOME RD SCAPPOOSE, OR

(10) STATIC WATER LEVEL:
384 ft. below land surface. Date 12/27/02
Artesian pressure lb. per square inch Date

(11) WATER BEARING ZONES:
Depth at which water was first found 450

From	To	Estimated Flow Rate	SWL
450	460	25 gpm	384

(12) WELL LOG:
Ground Elevation

Material	From	To	SWL
Topsoil	0	1	
Sticky red-brown clay	1	17	
Brown cly.	17	44	
Red-brown clay	44	64	
Gray-brown decomp basalt	64	112	
Gray-brown basalt,muddy	112	234	
Black basalt	234	252	
Hard gray-black basalt	252	277	
Gray-brown basalt	277	374	
Black basalt	374	399	
Gray-brown basalt	399	409	
Black basalt	409	427	
Gray-brown basalt	427	465	384

Date started 12/13/02 Completed 12/27/02

(unbonded) Water Well Constructor Certification:

I certify that the work I performed on the construction, alteration, or abandonment of this well is in compliance with Oregon water supply well construction standards. Materials used and information reported above are true to the best of my knowledge and belief.

WWC Number 1805
Signed Dwayne Bigby Date 12/27/02

(bonded) Water Well Constructor Certification:

I accept responsibility for the construction, alteration, or abandonment work performed on this well during the construction dates reported above. All work performed during this time is in compliance with Oregon water supply well construction standards. This report is true to the best of my knowledge and belief.

WWC Number 1266
Signed Date 12/27/02

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Figure 2.1. Example of well report from Dutch Canyon displaying detailed lithologic, location data, water-bearing zone information, and well test information.

2.2.1.1 Well Locations and Elevations

Locating water wells was critical in order to properly identify rock and hydrostratigraphic units from well log descriptions and existing geologic mapping. All well logs have fields for site address, tax lot, and location in the Township and Range system. When an address or tax lot was recorded, which was more common for wells drilled since the early 1980s, the location of the house was assumed to be the well location. This assumption is supported by the high percentage of wells located in close proximity to the property owner's home, observed during fieldwork in 2010 and 2011.

However, many wells in Dutch Canyon were drilled prior to the 1980s and often do not contain a physical address, but rather a rural route and box number. Nearly 40% of these earlier records also failed to provide ¼ section information, meaning that the most precise location for these wells was within a given section (one square mile in area), which could yield horizontal distance errors greater than 800 meters in any direction from the middle point of the section. Many areas in Dutch Canyon also have relief greater than 100 meters within one square mile, meaning that the use of well reports with poor location precision could potentially provide major errors in calculating elevations of lithologic units and contacts. In an effort to accurately locate wells without suitable location information listed on their well log reports, an internet search on the property owner listed on the well report was done, typically using the website Spokeo.com, which compiles address locations for individuals through time. In most cases, a physical address for the listed owner could not be found, but 12 well logs were located to specific addresses using this technique. Universal Transverse Mercator (UTM) coordinates for these locations were found by imputing the address into Google Earth and locating the house. Elevations were obtained from the available DEM for the area, which has a resolution of 10 m (1/3-arc second). All wells sampled during fieldwork were located with a Garmin differential GPS unit either on the top of the well casing or on the ground close to the well. Elevation measurements taken in the field via GPS were found to be within 10 m of the elevations obtained from the DEM model.

Where a well log did not provide an address but did list the ¼ or ¼- ¼ section for the home, the maximum error in locating the well was reduced, allowing for a greater precision in estimating surface elevations. For these locations, an aerial view from Google Earth was found and, if possible, a location could be determined visually. If multiple homes were found within the area, the mid-point of the ¼ or ¼, ¼ section was used for the well location. If there was less than 10 meters of elevation change in the ¼ section, the mid-point location and elevation was assumed to be sufficiently accurate. If the range of elevation within the area was greater than 10 meters, the center point was determined to have a significant chance of providing an error in lithology elevation and the well record was not used. In many cases, the elevation range far exceeded 10 meters.

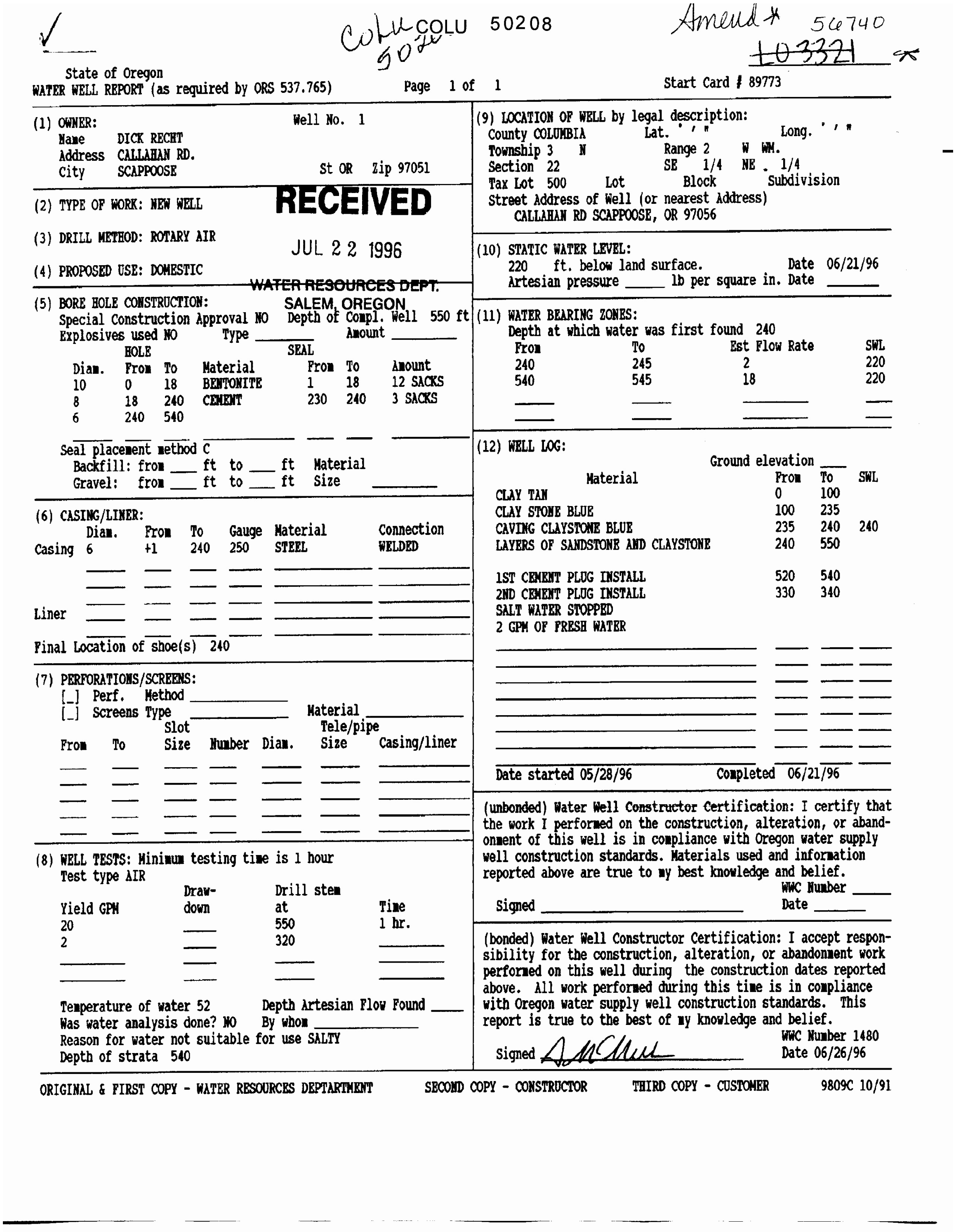
2.2.2.2 Determination of Lithologies and Water-bearing Units from Well Logs

The reliability of the well log descriptions was ascertained based on the level of detail shown in the log, comparison to nearby logs, and comparison to the published geologic map (Madin and Niewendorp, 2008) and field observations. In some cases, well logs provided detailed descriptions, differentiating units less than one meter thick while in other cases, only one rock type was listed over an interval of 50 or even 100 meters.

Occasionally, these well reports were located close to one another, and were drilled into the same unit (Fig. 2.2a, b)

Lithology listed on the well report was often incorrect or inaccurate. For example, well reports for many sites located in areas with basalt would describe the rock as sandstone. This is an understandable mistake for a driller without geologic training as much of the basalt in the area is heavily weathered and the reddish-brown weathering rinds can easily be mistaken for sandstone. However, as sandstone is the underlying rock to the Wapshilla Ridge member, the elevation of the well reports was critical to proper identification. After two summers of fieldwork and comparing logs in a given area, it was assumed that a well log that described sandstone present at an elevation above 200 meters amsl was describing basalt. Potential errors on the contact between the basalt and sandstone in these wells are likely high, but often a color difference would be noted.

Color descriptions were found quite useful in differentiating units as red or brown silt to sand unit was often present above a blue and grey sandstone. This observation is consistent with past lithologic descriptions of the Scappoose Formation (Ketrenos, 1986, Van Atta and Kelty, 1985) as having an arkosic, non-marine upper portion overlying a darker marine unit.



✓

Colu 502 COLU 50208

Amend * 56740

~~L03321~~ *

State of Oregon
WATER WELL REPORT (as required by ORS 537.765)

Page 1 of 1

Start Card # 89773

(1) OWNER: Well No. 1
Name DICK RECHT
Address CALLAHAN RD.
City SCAPPOOSE St OR Zip 97051

RECEIVED
JUL 22 1996
WATER RESOURCES DEPT.
SALEM, OREGON

(2) TYPE OF WORK: NEW WELL

(3) DRILL METHOD: ROTARY AIR

(4) PROPOSED USE: DOMESTIC

(5) BORE HOLE CONSTRUCTION:
Special Construction Approval NO Depth of Compl. Well 550 ft
Explosives used NO Type ____ Amount ____

HOLE			SEAL			
Diam.	From	To	Material	From	To	Amount
10	0	18	BENTONITE	1	18	12 SACKS
8	18	240	CEMENT	230	240	3 SACKS
6	240	540				

Seal placement method C
Backfill: from ___ ft to ___ ft Material
Gravel: from ___ ft to ___ ft Size ____

(6) CASING/LINER:

	Diam.	From	To	Gauge	Material	Connection
Casing	6	+1	240	250	STEEL	WELDED
Liner						

Final Location of shoe(s) 240

(7) PERFORATIONS/SCREENS:
[_] Perf. Method ____
[_] Screens Type ____ Material ____

From	To	Slot Size	Number	Diam.	Tele/pipe Size	Casing/liner

(8) WELL TESTS: Minimum testing time is 1 hour
Test type AIR

Yield GPM	Draw-down	Drill stem at	Time
20		550	1 hr.
2		320	

Temperature of water 52 Depth Artesian Flow Found ____
Was water analysis done? NO By whom ____
Reason for water not suitable for use SALTY
Depth of strata 540

(9) LOCATION OF WELL by legal description:
County COLUMBIA Lat. ° ' " Long. ° ' "
Township 3 N Range 2 W WM.
Section 22 SE 1/4 NE 1/4
Tax Lot 500 Lot Block Subdivision
Street Address of Well (or nearest Address)
CALLAHAN RD SCAPPOOSE, OR 97056

(10) STATIC WATER LEVEL:
220 ft. below land surface. Date 06/21/96
Artesian pressure ____ lb per square in. Date ____

(11) WATER BEARING ZONES:
Depth at which water was first found 240

From	To	Est Flow Rate	SWL
240	245	2	220
540	545	18	220

(12) WELL LOG:
Ground elevation ____

Material	From	To	SWL
CLAY TAN	0	100	
CLAY STONE BLUE	100	235	
CAVING CLAYSTONE BLUE	235	240	240
LAYERS OF SANDSTONE AND CLAYSTONE	240	550	
1ST CEMENT PLUG INSTALL	520	540	
2ND CEMENT PLUG INSTALL	330	340	
SALT WATER STOPPED			
2 GPM OF FRESH WATER			

Date started 05/28/96 Completed 06/21/96

(unbonded) Water Well Constructor Certification: I certify that the work I performed on the construction, alteration, or abandonment of this well is in compliance with Oregon water supply well construction standards. Materials used and information reported above are true to my best knowledge and belief.
WWC Number ____
Signed ____ Date ____

(bonded) Water Well Constructor Certification: I accept responsibility for the construction, alteration, or abandonment work performed on this well during the construction dates reported above. All work performed during this time is in compliance with Oregon water supply well construction standards. This report is true to the best of my knowledge and belief.
WWC Number 1480
Signed Date 06/26/96

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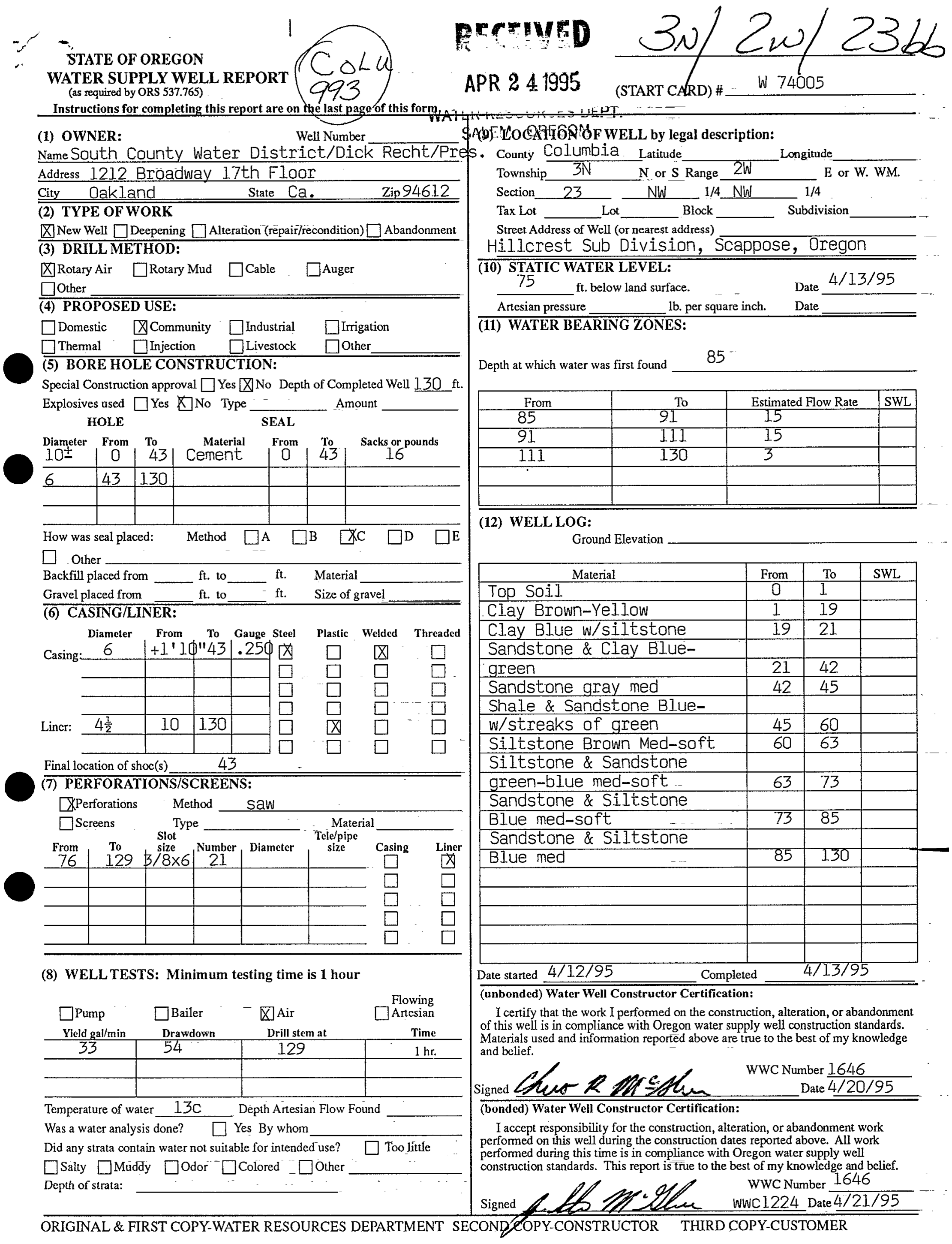
Figure 2.2a.



STATE OF OREGON
WATER SUPPLY WELL REPORT
(as required by ORS 537.765)
Instructions for completing this report are on the last page of this form.

Colu
993

RECEIVED
APR 2 4 1995
WATER RESOURCES DEPT.
SALEM, OREGON

3N/ 2W/ 23bb

(START CARD) # W 74005

(1) OWNER: Well Number
Name South County Water District/Dick Recht/Pres.
Address 1212 Broadway 17th Floor
City Oakland State Ca. Zip 94612

(2) TYPE OF WORK
☒ New Well ☐ Deepening ☐ Alteration (repair/recondition) ☐ Abandonment

(3) DRILL METHOD:
☒ Rotary Air ☐ Rotary Mud ☐ Cable ☐ Auger
☐ Other

(4) PROPOSED USE:
☐ Domestic ☒ Community ☐ Industrial ☐ Irrigation
☐ Thermal ☐ Injection ☐ Livestock ☐ Other

(5) BORE HOLE CONSTRUCTION:
Special Construction approval ☐ Yes ☒ No Depth of Completed Well 130 ft.
Explosives used ☐ Yes ☒ No Type Amount

HOLE			SEAL			
Diameter	From	To	Material	From	To	Sacks or pounds
10±	0	43	Cement	0	43	16
6	43	130				

How was seal placed: Method ☐ A ☐ B ☒ C ☐ D ☐ E
☐ Other
Backfill placed from ft. to ft. Material
Gravel placed from ft. to ft. Size of gravel

(6) CASING/LINER:

	Diameter	From	To	Gauge	Steel	Plastic	Welded	Threaded
Casing:	6	+1'10"	43	.250	☒	☐	☒	☐
					☐	☐	☐	☐
					☐	☐	☐	☐
					☐	☐	☐	☐
Liner:	4½	10	130		☐	☒	☐	☐
					☐	☐	☐	☐

Final location of shoe(s) 43

(7) PERFORATIONS/SCREENS:
☒ Perforations Method saw
☐ Screens Type Material

From	To	Slot size	Number	Diameter	Tele/pipe size	Casing	Liner
76	129	3/8x6	21			☐	☒
						☐	☐
						☐	☐
						☐	☐
						☐	☐

(8) WELL TESTS: Minimum testing time is 1 hour

☐ Pump ☐ Bailer ☒ Air ☐ Flowing Artesian

Yield gal/min	Drawdown	Drill stem at	Time
33	54	129	1 hr.

Temperature of water 13c Depth Artesian Flow Found
Was a water analysis done? ☐ Yes By whom
Did any strata contain water not suitable for intended use? ☐ Too little
☐ Salty ☐ Muddy ☐ Odor ☐ Colored ☐ Other
Depth of strata:

(9) LOCATION OF WELL by legal description:
County Columbia Latitude Longitude
Township 3N N or S Range 2W E or W. WM.
Section 23 NW 1/4 NW 1/4
Tax Lot Lot Block Subdivision
Street Address of Well (or nearest address)
Hillcrest Sub Division, Scappose, Oregon

(10) STATIC WATER LEVEL:
75 ft. below land surface. Date 4/13/95
Artesian pressure lb. per square inch. Date

(11) WATER BEARING ZONES:

Depth at which water was first found 85

From	To	Estimated Flow Rate	SWL
85	91	15	
91	111	15	
111	130	3	

(12) WELL LOG:
Ground Elevation

Material	From	To	SWL
Top Soil	0	1	
Clay Brown-Yellow	1	19	
Clay Blue w/siltstone	19	21	
Sandstone & Clay Blue-			
green	21	42	
Sandstone gray med	42	45	
Shale & Sandstone Blue-			
w/streaks of green	45	60	
Siltstone Brown Med-soft	60	63	
Siltstone & Sandstone			
green-blue med-soft	63	73	
Sandstone & Siltstone			
Blue med-soft	73	85	
Sandstone & Siltstone			
Blue med	85	130	

Date started 4/12/95 Completed 4/13/95

(unbonded) Water Well Constructor Certification:

I certify that the work I performed on the construction, alteration, or abandonment of this well is in compliance with Oregon water supply well construction standards. Materials used and information reported above are true to the best of my knowledge and belief.

WWC Number 1646
Signed Date 4/20/95

(bonded) Water Well Constructor Certification:

I accept responsibility for the construction, alteration, or abandonment work performed on this well during the construction dates reported above. All work performed during this time is in compliance with Oregon water supply well construction standards. This report is true to the best of my knowledge and belief.

WWC Number 1646
Signed WWC1224 Date 4/21/95

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Figure 2.2b: Well reports drilled in close proximity to each other which contain different quality of description. The well report in Figure 2.2a (previous page) lists few lithologic differences while the report in 2.2b has greater detail.

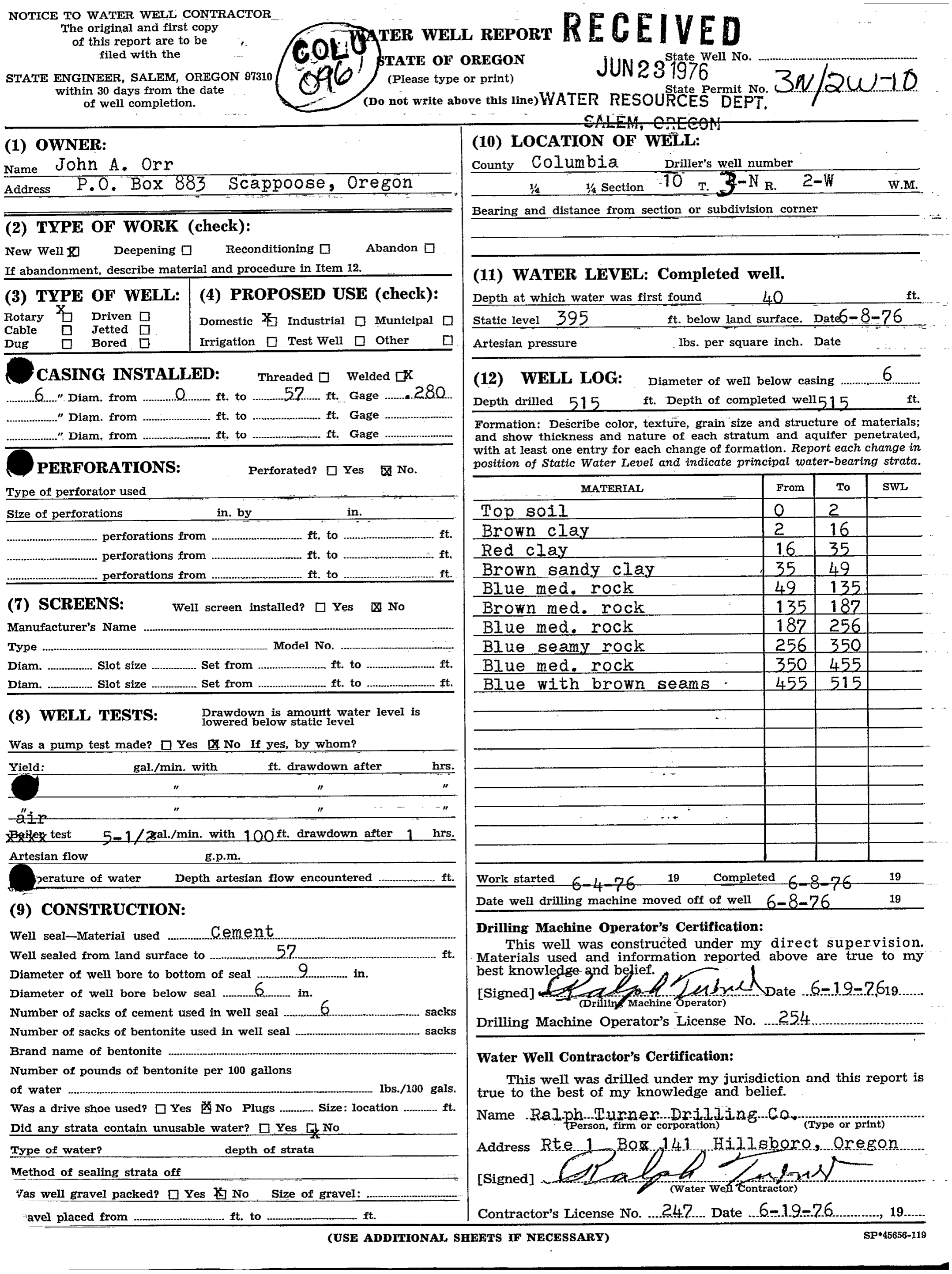
Lithologic data from well reports were imported into RockWorks 15 (RockWare, 2008) to assist in modeling the geology of the area. The RockWorks modeling program itself was also a useful tool to refine the lithologic data in Dutch Canyon as anomalies in unit elevations could be easily detected and analyzed for possible errors. All well report information, as well as calculated values based on the information from the well report was included in a database that can be built upon and modified as new information arises.

2.2.2 Field Mapping

In addition to using the well reports, background information on the local geology was used to determine likely locations of units and the contacts between them. A bedrock and surfical geology map of the Dixie Mountain quadrangle (Madin and Niewendorp, 2008) included several cross-sections. This map included the southern portion of Dutch Canyon. As no chemical analysis of rocks and sediments were performed for this study, the identification of basalt units by Madin and Niewendorp (2008) via chemical analysis was assumed to be correct. Their map was also used to determine areas that may have been impacted by landslides.

The presence of private property throughout the field area made extensive field mapping impossible. However, field examination of estimated contacts was conducted as part of this study, primarily utilizing outcrops exposed in road cuts (Fig. 2.4).

Changes in topography were also noted as potentially indicative of lithologic changes, such as sloped areas indicating shale and silt bedrock and steeper gradients indicating more resistant sandstones or basalts. These observations were compared to local well log descriptions for verification.



NOTICE TO WATER WELL CONTRACTOR
The original and first copy
of this report are to be
filed with the
STATE ENGINEER, SALEM, OREGON 97310
within 30 days from the date
of well completion.

COLU
096

WATER WELL REPORT
STATE OF OREGON
(Please type or print)
(Do not write above this line)

RECEIVED
JUN 23 1976
WATER RESOURCES DEPT.
SALEM, OREGON

State Well No.
State Permit No. 3N/2W-10

(1) OWNER:

Name John A. Orr

Address P.O. Box 883 Scappoose, Oregon

(2) TYPE OF WORK (check):

New Well ☒ Deepening ☐ Reconditioning ☐ Abandon ☐

If abandonment, describe material and procedure in Item 12.

(3) TYPE OF WELL:

Rotary ☒ Driven ☐
Cable ☐ Jetted ☐
Dug ☐ Bored ☐

(4) PROPOSED USE (check):

Domestic ☒ Industrial ☐ Municipal ☐
Irrigation ☐ Test Well ☐ Other ☐

CASING INSTALLED: Threaded ☐ Welded ☒

6" Diam. from 0 ft. to 57 ft. Gage .280
" Diam. from ft. to ft. Gage
" Diam. from ft. to ft. Gage

PERFORATIONS: Perforated? ☐ Yes ☒ No.

Type of perforator used

Size of perforations in. by in.

perforations from ft. to ft.
perforations from ft. to ft.
perforations from ft. to ft.

(7) SCREENS: Well screen installed? ☐ Yes ☒ No

Manufacturer's Name

Type Model No.

Diam. Slot size Set from ft. to ft.
Diam. Slot size Set from ft. to ft.

(8) WELL TESTS: Drawdown is amount water level is lowered below static level

Was a pump test made? ☐ Yes ☒ No If yes, by whom?

Yield: gal./min. with ft. drawdown after hrs.
" " "
" " " "

~~Bailer~~ air test 5-1/2 gal./min. with 100 ft. drawdown after 1 hrs.

Artesian flow g.p.m.

[illegible]perature of water Depth artesian flow encountered ft.

(9) CONSTRUCTION:

Well seal—Material used Cement
Well sealed from land surface to 57 ft.
Diameter of well bore to bottom of seal 9 in.
Diameter of well bore below seal 6 in.
Number of sacks of cement used in well seal 6 sacks
Number of sacks of bentonite used in well seal sacks
Brand name of bentonite
Number of pounds of bentonite per 100 gallons of water lbs./100 gals.
Was a drive shoe used? ☐ Yes ☒ No Plugs Size: location ft.
Did any strata contain unusable water? ☐ Yes ☒ No
Type of water? depth of strata
Method of sealing strata off
Was well gravel packed? ☐ Yes ☒ No Size of gravel:
Gravel placed from ft. to ft.

(10) LOCATION OF WELL:

County Columbia Driller's well number

¼ ¼ Section 10 T. 3-N R. 2-W W.M.

Bearing and distance from section or subdivision corner

(11) WATER LEVEL: Completed well.

Depth at which water was first found 40 ft.
Static level 395 ft. below land surface. Date 6-8-76
Artesian pressure lbs. per square inch. Date

(12) WELL LOG: Diameter of well below casing 6

Depth drilled 515 ft. Depth of completed well 515 ft.

Formation: Describe color, texture, grain size and structure of materials; and show thickness and nature of each stratum and aquifer penetrated, with at least one entry for each change of formation. *Report each change in position of Static Water Level and indicate principal water-bearing strata.*

MATERIAL	From	To	SWL
Top soil	0	2	
Brown clay	2	16	
Red clay	16	35	
Brown sandy clay	35	49	
Blue med. rock	49	135	
Brown med. rock	135	187	
Blue med. rock	187	256	
Blue seamy rock	256	350	
Blue med. rock	350	455	
Blue with brown seams	455	515	

Work started 6-4-76 19 Completed 6-8-76 19

Date well drilling machine moved off of well 6-8-76 19

Drilling Machine Operator's Certification:

This well was constructed under my direct supervision. Materials used and information reported above are true to my best knowledge and belief.

[Signed] Ralph Turner (Drilling Machine Operator) Date 6-19-76 19

Drilling Machine Operator's License No. 254

Water Well Contractor's Certification:

This well was drilled under my jurisdiction and this report is true to the best of my knowledge and belief.

Name Ralph Turner Drilling Co. (Person, firm or corporation) (Type or print)

Address Rte 1 Box 141 Hillsboro, Oregon

[Signed] Ralph Turner (Water Well Contractor)

Contractor's License No. 247 Date 6-19-76, 19

(USE ADDITIONAL SHEETS IF NECESSARY) SP*45656-119

Figure 2.3. Well report from Dutch Canyon listing only "rock" and a color for lithology. Included as an example of limitations in using well reports to identify units.

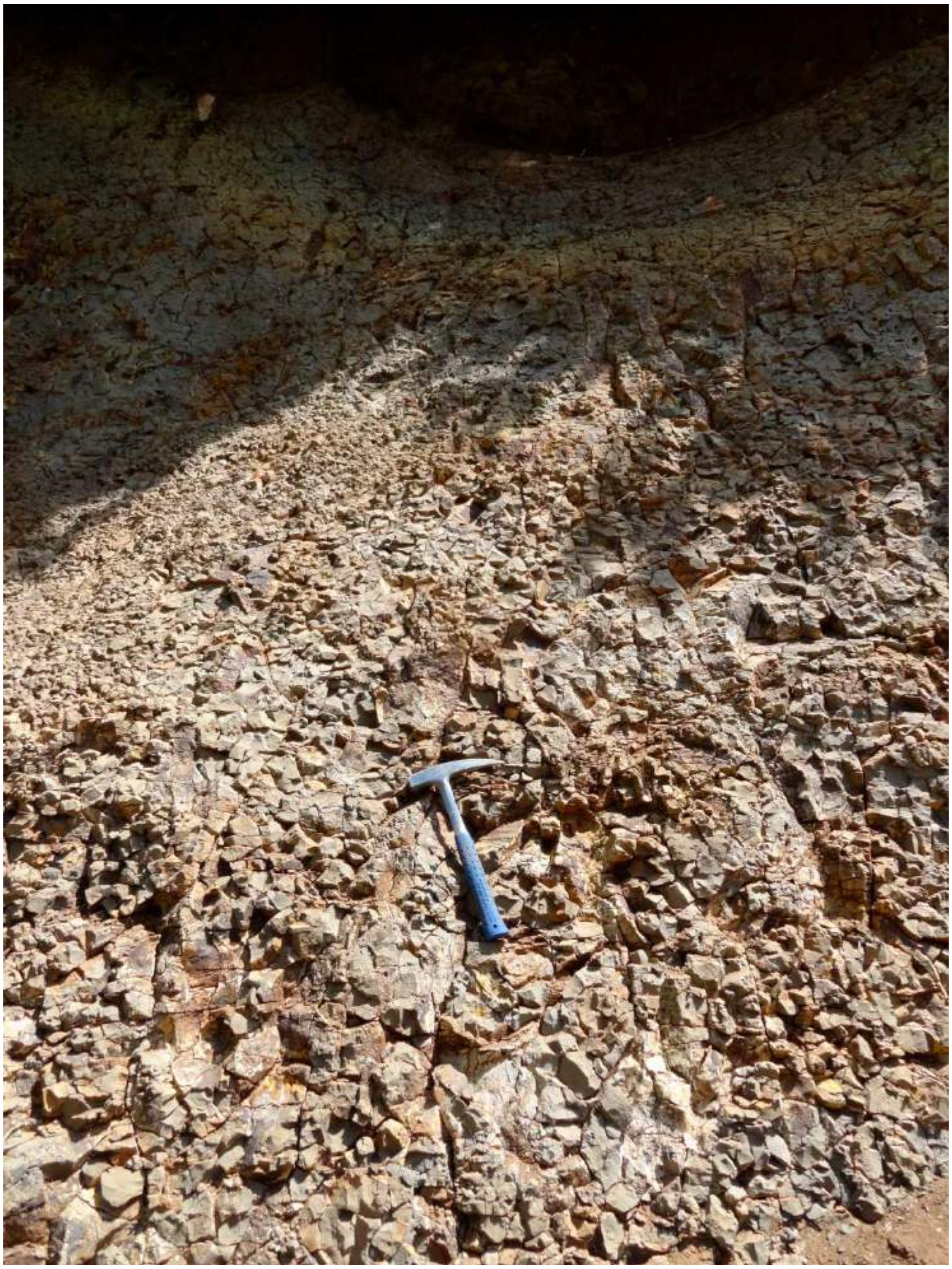


Figure 2.4. Outcrop exposure of Wapshilla Ridge basalt along the northern ridge of Dutch Canyon.

2.2.3 Determination of Hydraulic Characteristics for Water-Bearing Units

Hydrogeologic parameters for individual aquifer units were determined from the well log reports where sufficient hydraulic information was provided. The most readily available hydraulic data were well yields (recorded in gallons per minute (gpm)) provided on many, though not all, well logs. Specific capacity, or the yield of a well divided by its drawdown, could be calculated if both types of information were listed, although this is not the case for the majority of well reports. From the specific capacity, the transmissivity of a given unit can be estimated. Transmissivity is defined as the discharge per unit width of an aquifer under a unit hydraulic gradient. It can be derived from the Cooper-Jacob (1946) solution for flow in a nonleaky confined aquifer, which can be expressed as:

$$T = \frac{2.3Q}{4\pi\Delta s} \tag{2.1a}$$

$$S = \frac{2.25Tt_0}{r^2} \tag{2.1b}$$

where Q is constant discharge rate or well yield, r is pumped well radius, S is storativity, Δs is (log) drawdown in the well, T is transmissivity, and t is time. From these equations, Driscoll (1986) assumed typical values to develop formulas for estimating transmissivity from specific capacity (Q/s_w):

$$T = 2000(Q/s_w) \text{ for a confined aquifer} \tag{2.2}$$

$$T = 1500(Q/s_w) \text{ for an unconfined aquifer} \tag{2.3}$$

The storage coefficient, or storativity (S) is the volume of water that a permeable unit absorbs or expels from storage per unit surface area per unit change in head (Fetter, 1980). The specific storage (S_s) is the amount of water per unit volume of a saturated formation that is stored or expelled from storage owing to compressibility of the mineral skeleton and the pore water per unit change in head. Specific storage is calculated (Jacob 1940, 1950; Cooper 1966) by:

$$S_s = p_w g(\alpha + n\beta) \qquad (2.4)$$

where p_w is the density of water, g is the gravitational constant (9.807 m/s^2), α is the compressibility of the aquifer skeleton, n is porosity, and β is the compressibility of water. The unit for compressibility is the inverse of pressure. The compressibility of water ranges from 4.65×10^{-10} m^2/N at 15°C to 4.5×10^{-10} m^2/N at 25°C (Batu, 1998). It should be noted that this trend reverses at 45°C, although that is outside the range of normal and observed water temperatures in the area. Specific storage can be used to calculate aquifer storativity, which is the product of specific storage and aquifer thickness. Values for the vertical compressibility of rock matrix reported in Table 2.1 were taken from Fetter (2001) and Domenico and Mifflin (1965).

Table 2.1: Vertical compressibility of various lithologies. Modified from Fetter (2001) and Domenico and Mifflin (1965).

Material	Coefficient of Vertical Compressibility m^2/N
Plastic clay	2×10^{-6} - 2.6×10^{-7}
Stiff clay	2.6×10^{-7} - 1.3×10^{-7}
Medium-hard clay	1.3×10^{-7} - 6.9×10^{-8}
Loose sand	1×10^{-7} - 5.2×10^{-8}
Dense sand	2×10^{-8} - 1.3×10^{-8}
Dense, sandy gravel	1×10^{-8} - 5.2×10^{-9}
Rock, fissured	6.9×10^{-10} - 3.3×10^{-10}
Rock, sound	less than 3.3×10^{-10}
Water at 25 C	4.8×10^{-10}

As no previous study in the area evaluated the porosity of the Scappoose Formation and this study did not conduct sediment analysis, effective porosity for the Scappoose Formation is estimated from accepted literature values (Walton, 1987; Domenico and Schwartz, 1990):

Table 2.2: Generalized effective porosity values for lithologies common in Dutch Canyon (Walton, 1987; Domenico and Schwartz, 1990).

Aquifer Matrix	Effective Porosity, n_e (%)
Clay	1-2
Silt	1-30
Sandstone, medium-grained	15-30
Sandstone, fine-grained	10-30
Sandstone, coarse-grained	20-35
Basalt, fractured	10

2.2.4 Determination of Groundwater Flow Directions

Mapping of water elevations (head) is used to determine the direction of groundwater flow and may help distinguish which flow zone a given well is screened in. Anomalous changes in groundwater elevations over short distances can also be indicative of structures like faults and landslide complexes.

In order to determine a general flow regime for groundwater in Dutch Canyon, the depths of first water and static water levels were obtained from water well reports and then subtracted from the calculated ground elevations to determine the groundwater elevation at each well site. In many well reports, the elevation of first water is often not the same as the static water-level elevation; first water is most often higher in the well. The area is known for low yields and occasionally dry wells and drillers may be eager to report any water present. Wells reporting first water above static water often describe the first water as “trace” or less than one gallon (3.78 liters) per minute with the water-bearing zone less than 1 meter thick. The first water reports in these wells may not indicate the elevation of the aquifer but rather a small concentration of water in a permeable lens or fractured rock.

The static water level value in a confined aquifer is not indicative of the aquifer elevation, but rather the potentiometric surface (hydraulic head) elevation. Groundwater flows from higher to lower hydraulic head, so the trend of static water levels over an area should provide a coarse, composite measure of groundwater flow direction. Both first water and static water levels were mapped to compare the results between the methods. Not every well log included both static water and first water measurements.

The elevation values for first water and static water levels were mapped onto the DEM for Dutch Canyon and contour map constructed using RockWorks15. The gridding technique used for creating these maps was inverse distance with a weighting exponent of 2.00, allowing for a mixture of local and global effects on the map. The grid was based on eight points, meaning a maximum of eight data points were used in computing the grid node value. A smoothing technique averaging elevations between three adjacent nodes was applied.

2.2.8 Determination of Area Hydrologic Parameters

To investigate the hydrology of Dutch Canyon, precipitation and stream gauge records were located online. Dutch Canyon has over 300 meters of relief with the lower elevations likely to receive less precipitation than the higher elevations due to orographic effects. To account for this difference, two weather stations, one located in the Scappoose Industrial Airpark (K1S4) at 25 meters elevation and one located 11 km southwest of Scappoose in North Plains (ID# US10ORWS0025) at 440 meters elevation were used to estimate average precipitation throughout the study area. As weather systems are mainly regional, it is assumed that the North Plains precipitation record was reflective of precipitation at similar elevations within the study area as both areas are located just to the west of the Portland Hills Fault.

No stream gauge exists on the South Fork Scappoose Creek and the discharge is impacted by impoundment in the upper reaches. However, stream discharge measurements from a nearby gaging station in the Tualatin Mountains were used to estimate groundwater recharge rates using the seasonal baseflow recession method (Meyboom, 1961). The station (USGS 14205400) is located along the East Fork Dairy Creek in the northeastern corner of Washington County, 11 km southwest (230 degrees) of Dutch Canyon at the turn off to Otto Miller Road. Dairy Creek shares a watershed boundary with the South Fork Scappoose Creek (the southern boundary of the latter) and the area is included on the same geological quadrangle map (Madin and Niewendorp, 2008), so the geology and hydrogeology of the recharge area along the upper reaches may be assumed to be similar. The surface area for the East Fork Dairy Creek subwatershed above the USGS gaging station is 8,750ha (33.8 mi^2, 87,500,000 m^2)

The Meyboom (1961) method utilizes stream hydrographs for two consecutive years, 2009 and 2010 in this case. A plot of the stream hydrograph containing time on an arithmetic scale and discharge on a logarithmic scale will yield a straight line for baseflow recession. For this area, the recessions were considered to start when streamflow sourced from winter rains stopped and to end at the start of the rainy season the next autumn. The total potential groundwater discharge is the volume of water that would be discharged during a complete groundwater recession which is calculated by

$$V_{tp} = \frac{Q_0 t_1}{2.3026} \tag{2.5}$$

where V_{tp} is the volume of the total potential groundwater discharge (m^3), Q_0 is the baseflow at the start of the recession (m^3 s^{-1}) and $t_1$is the time is takes the baseflow to go from Q_0 to 0.1 Q_0 (s).

As per Fetter (2001), if the remaining potential groundwater discharge at the end of a recession is determined along with the total potential groundwater discharge at the beginning of the next recession, the difference between the two is the groundwater recharge that took place between recessions. The amount of potential baseflow (V_t) remaining after the start of a baseflow recession is determined by

$$V_t = \frac{V_{tp}}{10^{t/t_1}} \tag{2.6}$$

2.3 Results and Discussion

The physical hydrogeology of Dutch Canyon was assessed mainly through the collation of 196 well reports from Columbia, Washington, and Multnomah counties. The well reports contained lithologic information from which individual hydrostratigraphic units could be identified and characterized. Aquifer transmissivities were calculated using recorded values of drawdown and pumping rate from 27 wells. The majority of well logs either did not include enough information to make the determination or reported results from “air” tests with drawdowns which were likely to have been based on the depth of the drill stem rather than actual water level measurements and so were not deemed reliable. Aquifer porosities and storage coefficients were estimated for individual hydrostratigraphic units based on lithologic descriptions, average thickness, and generalized compressibilities obtained from the literature. Most well logs contained depth-to-water measurements that were used, along with DEM elevations, to determine groundwater elevations and general flow direction. Well locations and yield are shown in Figure 2.5.

2.3.1 General Hydrostratigraphy

Hydrogeologic units are defined based on stratigraphic and hydraulic characteristics. Within Dutch Canyon, hydrogeologic units can be generally divided between the sedimentary Scappoose Formation, which is further divided into four hydrostratigraphic units (only the upper three of which were drilled by area wells), and the overlying Grande Ronde Basalt Formation, for which four hydrostratigraphic units are defined for this study (Table 2.3).

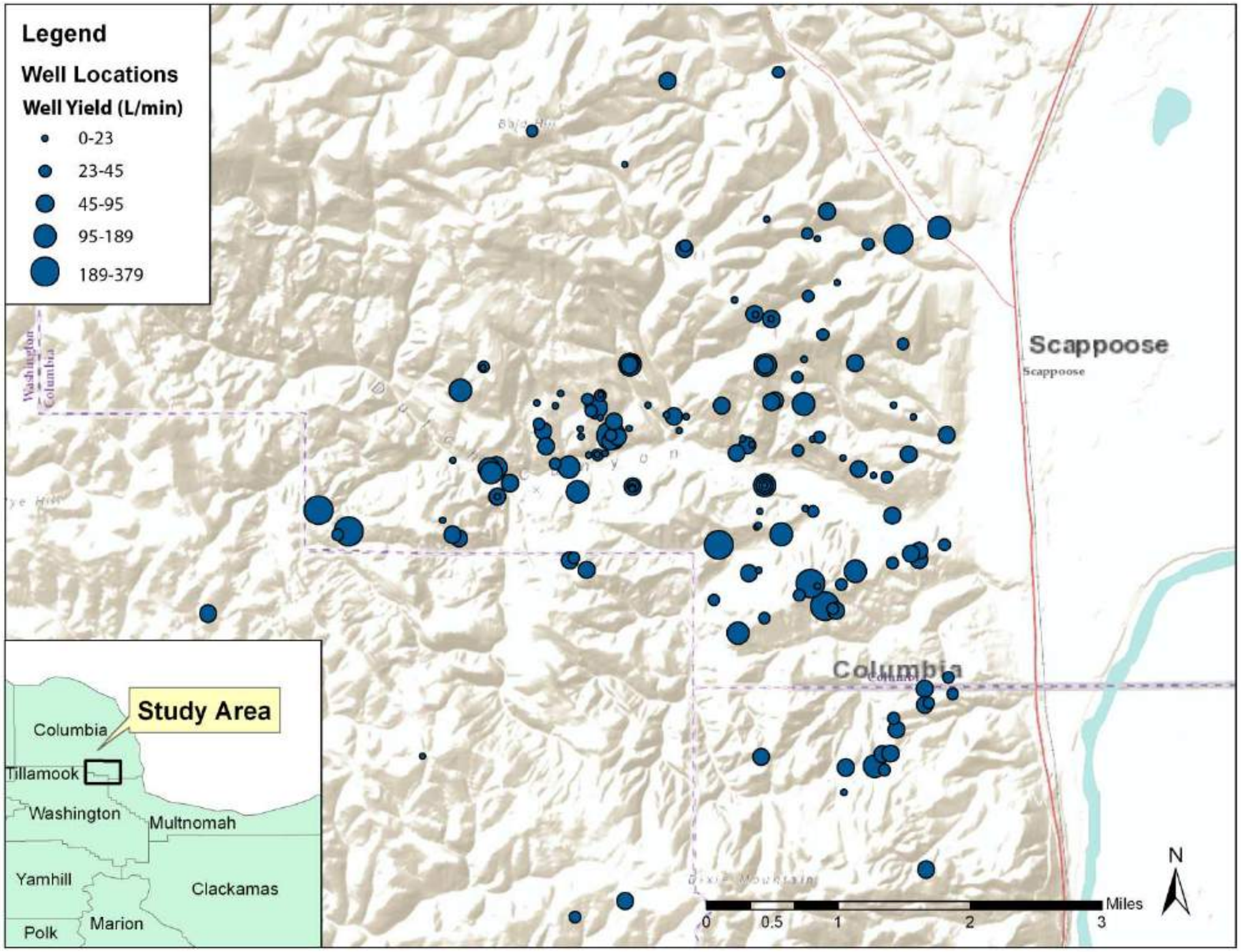
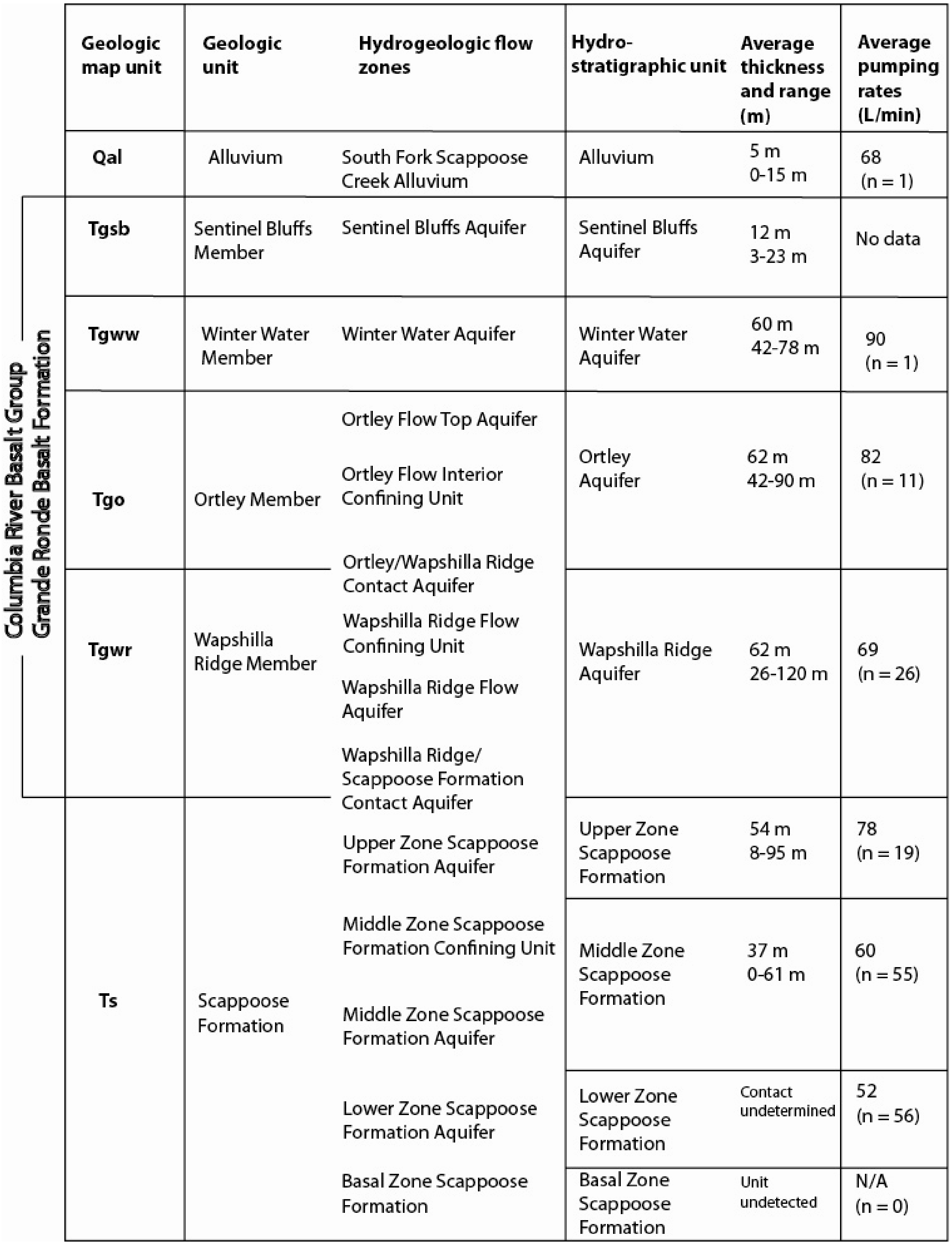


Figure 2.5. Well locations and yields in Dutch Canyon. Yield amounts are represented by relative circle size with smaller yields in front over larger yields. Overlapping wells are locations where multiple wells were installed on the same property.

Table 2.3. Geologic and hydrogeologic units within Dutch Canyon.



	Geologic map unit	Geologic unit	Hydrogeologic flow zones	Hydro-stratigraphic unit	Average thickness and range (m)	Average pumping rates (L/min)
	Qal	Alluvium	South Fork Scappoose Creek Alluvium	Alluvium	5 m 0-15 m	68 (n = 1)
Columbia River Basalt Group Grande Ronde Basalt Formation	Tgsb	Sentinel Bluffs Member	Sentinel Bluffs Aquifer	Sentinel Bluffs Aquifer	12 m 3-23 m	No data
	Tgww	Winter Water Member	Winter Water Aquifer	Winter Water Aquifer	60 m 42-78 m	90 (n = 1)
	Tgo	Ortley Member	Ortley Flow Top Aquifer Ortley Flow Interior Confining Unit	Ortley Aquifer	62 m 42-90 m	82 (n = 11)
	Tgwr	Wapshilla Ridge Member	Ortley/Wapshilla Ridge Contact Aquifer Wapshilla Ridge Flow Confining Unit Wapshilla Ridge Flow Aquifer Wapshilla Ridge/Scappoose Formation Contact Aquifer	Wapshilla Ridge Aquifer	62 m 26-120 m	69 (n = 26)
	Ts	Scappoose Formation	Upper Zone Scappoose Formation Aquifer	Upper Zone Scappoose Formation	54 m 8-95 m	78 (n = 19)
			Middle Zone Scappoose Formation Confining Unit Middle Zone Scappoose Formation Aquifer	Middle Zone Scappoose Formation	37 m 0-61 m	60 (n = 55)
			Lower Zone Scappoose Formation Aquifer	Lower Zone Scappoose Formation	Contact undetermined	52 (n = 56)
			Basal Zone Scappoose Formation	Basal Zone Scappoose Formation	Unit undetected	N/A (n = 0)

2.3.2 Scappoose Formation Hydrostratigraphy

The Scappoose Formation has several distinct lithologic units noted by previous workers (e.g., Warren and Norbisrath, 1946; Van Atta and Kelty, 1985; and Ketrenos, 1986). Although there is undoubtedly preferential flow through various beds in the Scappoose Formation, the overall heterogeneity within the Scappoose Formation and lack of detail in descriptions makes it difficult to delineate flow units beyond three corresponding to the broad lithologic units previously defined. It is assumed that groundwater flow occurs throughout the thickness of each of these units rather than preferentially through fractures. A series of cross-sections displaying the hydrostratigraphic units in Dutch Canyon are presented below (Fig. 2.6). Two cross-sections, A-A' (Fig. 2.7) and B-B' (Fig. 2.8) run north-south and another, C-C' (Fig. 2.9) runs west-east to display the hydrostratigraphy from ridge to valley floor to ridge as well as along the length of the canyon.

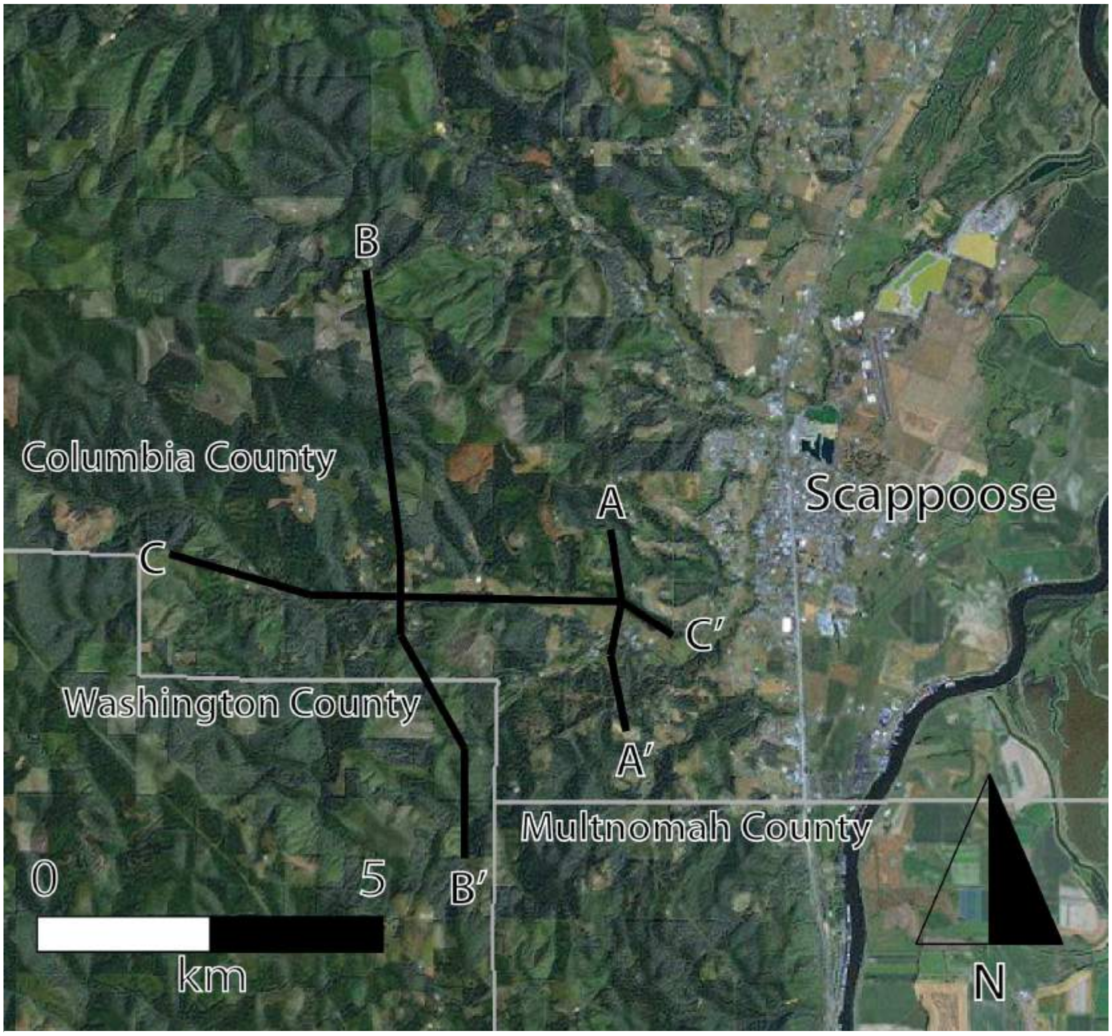


Figure 2.6: Location map of stratigraphic cross-sections in Dutch Canyon. The two North-South cross-sections represent the range in elevation within Dutch Canyon. C-C' represents the hydrogeology along the South Fork Scappoose Creek river valley.

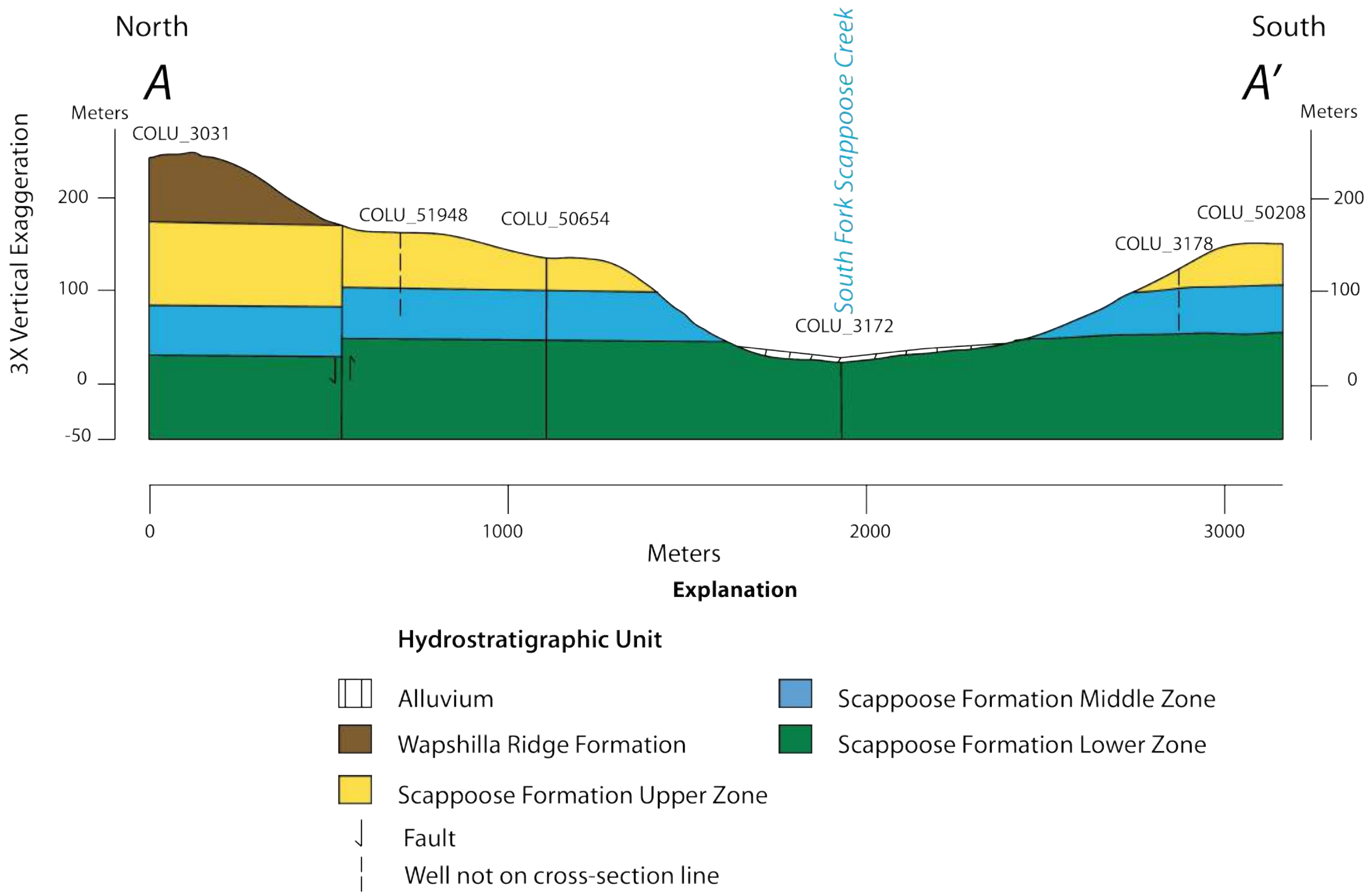


Figure 2.7. North-South cross-section (A-A’) of middle portion of Dutch Canyon made using RockWorks 15. An offset was noted in the well reports between COLU_3031 and COLU_50654 and was identified as a fault based on Marty (1983).

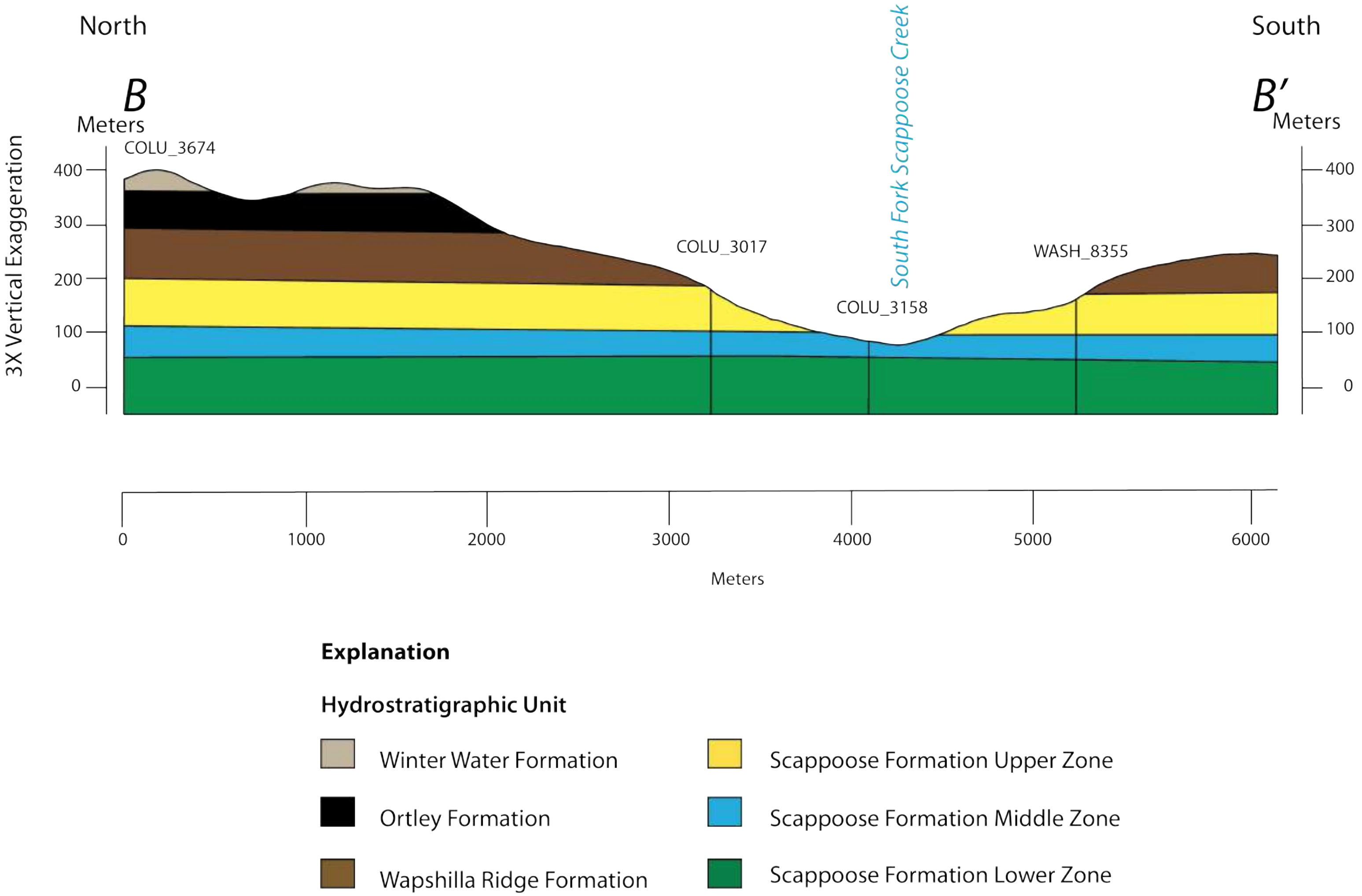


Figure 2.8. North-South cross-section of western portion of Dutch Canyon. Incision of South Fork Scappoose Creek is less prevalent than in cross section to the east. Scappoose Formation is not exposed at the surface.

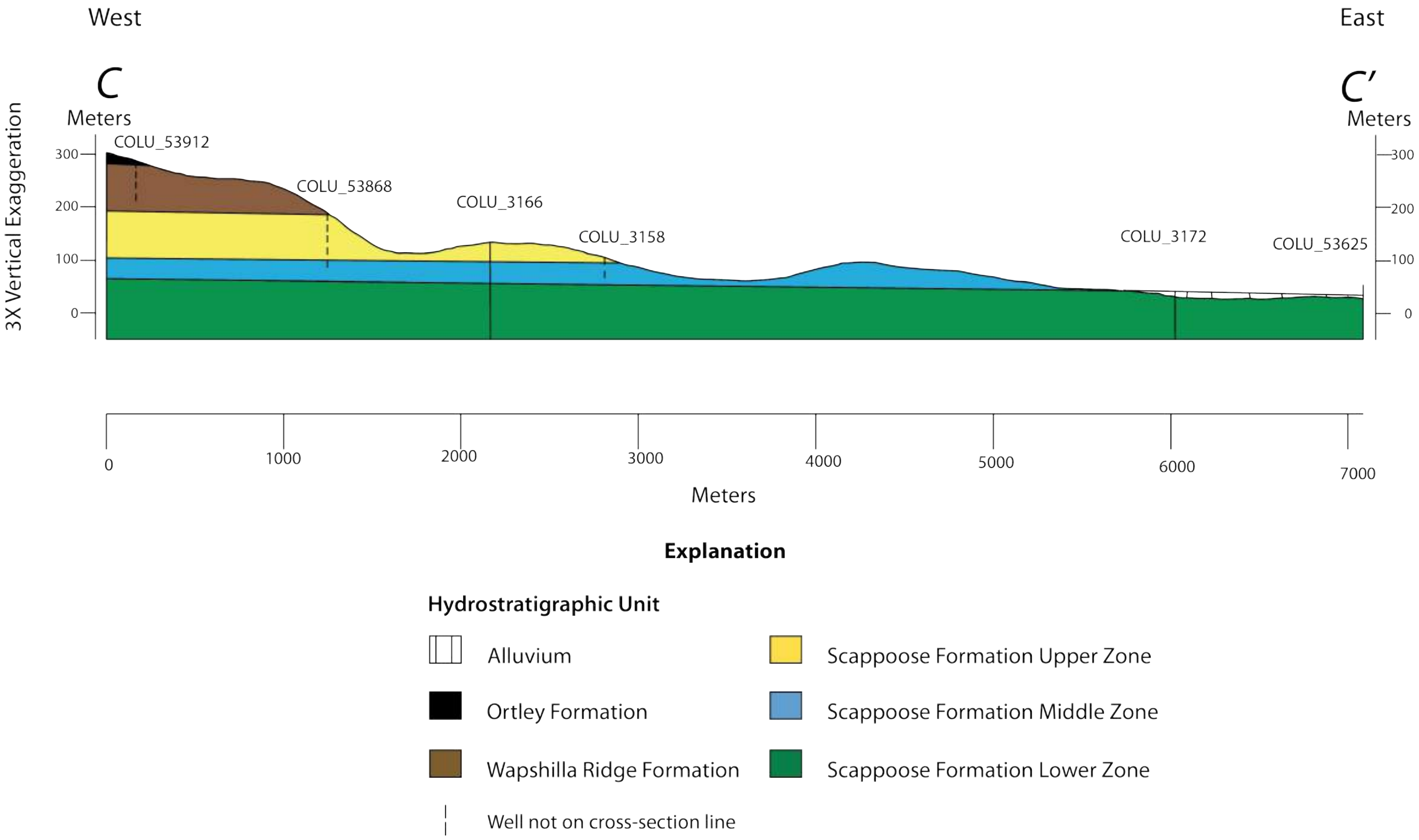


Figure 2.9. West-East cross-section of Dutch Canyon displaying stratigraphy of area within the South Fork Scappoose Creek valley.

2.3.2.1 Lower Scappoose Hydrostratigraphic Unit

The lowest water-bearing zone of the Scappoose Formation that could be determined from well reports occurs below 25 meters of elevation. No well logs reported drilling into the basalt conglomerate zone at the base of the Scappoose and extending to the contact with the underlying Pittsburg Bluffs Formation, as described by Warren and Norbisrath (1946) and Ketrenos (1986). Previous descriptions of that portion of the Scappoose Formation immediately overlying the conglomerate indicate that it is mainly comprised of non-marine tuffaceous and micaceous fine-grained sandstone (Ketrenos, 1986). In the area well reports, the lower unit is distinguished from the middle unit by a color change from blue to gray and is more often described as a sandstone rather than siltstone and claystone as is the case in the middle unit.

Reported yield tests on wells open to the lower Scappoose hydrostratigraphic unit were recorded between 1.9-57 liters (0.5-15 gallons) per minute up to an hour of pumping, most at less than 38 liters (10 gallons) per minute. In many cases, the well logs did not indicate the amount of drawdown for the well test so the pumping rate is assumed to be at a level that the well can sustain over an hour of pumping. This assumption is supported by the fact that the same driller used different rates of pumping at different wells rather than a standard rate. In well logs where drawdown was recorded ($n = 22$), water levels dropped between a low of 0.6 meters and a high of 126 meters over an hour, with an average drawdown of 34 meters over an hour.

Transmissivity values calculated from these pump test data (Table 2.4) ranged between 0.9 - 53 $m^2\ d^{-1}$, with an average of 18 $m^2\ d^{-1}$, similar to the average calculated for the other hydrogeologic units in the Scappoose Formation. Using an assumed average thickness of 100 meters and an effective porosity of 20%, based off the midpoint of the effective porosity of fine-grained sandstone in Table 2.2, an aquifer compressibility of 5.1×10^{-10} m^2/N, based on the mid-point of fissured rock from Table 2.1, specific storage was estimated at 5.9×10^{-6} and the aquifer storativity of the lower unit was estimated at 5.9×10^{-4}. As the base of the upper Scappoose hydrostratigraphic unit is not present in well reports, a thickness of 100 meters was used for the unit based on stratigraphic descriptions by Ketrenos (1986).

2.3.2.2 Middle Scappoose Hydrostratigraphic Unit

West of the Portland Hills Fault, the middle unit of the Scappoose Formation generally occurs at between 25 and 100 meters of elevation. Past work (Van Atta and Kelty, 1985) has identified the mid-section the Scappoose Formation as a marine siltstone and sandstone. Well reports typically describe this zone as a blue to green sandstone or siltstone of variable thickness, no greater than 80 meters. According to stratigraphic mapping by Ketrenos (1986) displayed in Figure 1.4, the southeastern most section that was measured (East Fork Nehalem Creek) contained no marine siltstone underlying the arkosic sansdstone, interpreted as the middle and upper units, respectively, in this study. The sections indicate much variability in the marine unit, which well reports support. The middle unit of the Scappoose Formation is locally topped by a blue clay layer typically several meters thick that separates the middle and upper Scappoose hydrostratigraphic units in many parts of the study area. Unit thickness measurements based on well reports are subject to blue or green color marker beds and presence of the overlying blue clay unit. If these properties were not noted on reports for wells suspected of being drilled into the middle unit, it was difficult to decipher contacts between units and reports were often not used for analysis. This unit outcrops in several locations along Dutch Canyon and Otto Miller Roads, showing a white to bluish-green appearance, with localized zones of (red) oxidation (Fig. 2.10).

Many wells in Dutch Canyon draw from the middle unit of the Scappoose Formation, but lateral variability in quality and quantity of water is high due to depositional variation between fine- and coarse-material. Pumping rates for well tests performed on wells open to the middle unit of the Scappoose Formation were highly variable, ranging from 53 liters (14 gallons) per minute over an hour of pumping to 114 liters (30 gallons) per minute. Estimates of transmissivity values for the unit range between 1.2 - 373 m^2 d^{-1}. Many of the well logs for wells open to this unit indicate low production with yields less than 38 liters (10 gallons) per minute and some occasional dry wells. In some well reports, a broken or fractured seam was sometimes responsible for providing a greater yield of water. Using an effective porosity of 15%, based off the same assumption of 20% in fine-grained sandstone in the lower unit minus 5% for a slightly lower percentage of effective porosity due to more clay throughout the middle unit than the lower unit, an average aquifer thickness of 37 meters, an aquifer compressibility of 5.1×10^{-10} m^2/N (Table 2.1), the storativity of the middle Scappoose unit is estimated at 2.1×10^{-4}.and specific storage was estimated at 5.7×10^{-6}. Well logs indicate localized presence of salty water within the middle and lower units of the Scappoose Formation, within both the sandstone and siltstone.

2.3.2.3 Upper Scappoose Hydrostratigraphic Unit

The upper Scappoose hydrostratigraphic unit ("upper Scappoose") varies from 0 to 110 m in thickness and is between 100 and 200 meters amsl throughout Dutch Canyon, west of the Portland Hills Fault and. Past work (Van Atta and Kelty, 1985) has identified this as an arkosic sandstone. The upper portion of the Scappoose Formation is typified in well logs as a brown to multicolored sandstone. It is often separated from the underlying middle Scappoose by a blue clay unit. The unit is overlain by the Wapshilla Ridge member of the Grande Ronde Basalt. Although individual well logs may identify discrete "water-bearing zones" one to four meters in thickness, separated by clay and shale interbeds, such zones do not appear to be laterally continuous. Therefore, the flow zone for this unit is considered to encompass the entire unit thickness.

Table 2.4: Transmissivity values for wells in Dutch Canyon sorted by unit. Twenty-seven of the 196 wells within Dutch Canyon had enough information listed to calcuate transmissivity values.

Site	Hydrostratigraphic Unit	Transmissivity (m^2 d^{-1})	Well Yield (L min^{-1})
COLU_3018	Wapshilla Ridge	2.6	42
COLU_3043	Scappoose upper	7.5	114
COLU_3028	Scappoose upper	99	76
WASH_8355	Scappoose upper	5.8	76
COLU_3138	Scappoose upper/middle Mix	1.9	34
COLU_3176	Scappoose middle (LS)	0.6	21
MULT_2115	Scappoose middle	1.2	57
COLU_3045	Scappoose middle	1.4	13
COLU_3025	Scappoose middle	3.4	57
COLU_3178	Scappoose middle	6.2	38
COLU_3137	Scappoose middle	26	61
COLU_3022	Scappoose middle	33	76
COLU_3158	Scappoose middle	75	170
COLU_3166	Scappoose middle	370	114
COLU_3011	Scappoose middle/lower Mix	0.1	4
COLU_3139	Scappoose middle/lower Mix	150	114
COLU_3155	Scappoose middle/lower Mix	190	57
COLU_52774	Scappoose lower	0.9	11
COLU_107	Scappoose lower	3.5	19
COLU_3163	Scappoose lower	4.1	38
COLU_3144	Scappoose lower	5.0	38
COLU_3145	Scappoose lower	6.2	38
COLU_3143	Scappoose lower	9.9	38
COLU_3141	Scappoose lower	25	57
COLU_3161	Scappoose lower	50	76
COLU_3026	Scappoose lower	53	114
COLU_3179	River alluvium	150	68

Figure 2.10. Exposure of middle portion of Scappoose Formation, near intersection between Otto Miller Road and Dutch Canyon Road, displaying slight blue color.

Well yield values for this unit are higher than the middle and lower Scappoose hydrostratigraphic units, ranging between 15 - 300 liters (2.6 - 80 gallons) per minute from driller well tests, with an average of 100 liters (26 gallons) per minute. The higher yield values are likely a result of the increased sorting of the sediments in the unit and higher sand to silt ratio than in the lower units. Estimates of transmissivity ranged from 5.8 - 99 m^2 d^{-1}, with only three wells providing sufficient data for calculation. Assuming an average thickness 54 meters and an effective porosity of 25%, based a coarser grain size than the middle and lower units, the storativity of the unit was estimated at 3.2 x 10^{-4} and specific storage was estimated at 5.9 x 10^{-6}.

2.3.3 Grande Ronde Basalt Formation Hydrostratigraphy

In general, CRBG lava flows typically consist of a dense flow interior and irregular flow tops and bottoms (Reidel, 2003). As a group, the CRBG is a stack of laterally extensive lava flows with relatively thin, permeable, productive zones at flow tops and flow bottoms separated by relatively thick flow interiors of low permeability (Fig. 2.11). Flow tops form as lava cools and hardens on the surface of the flow while the liquid interior continues to flow, which causes brecciation in the solidified flow top. Flow tops are also often vesiculated by escaping gases. Flow bottom textures are a result of fracturing from contact with the relatively cold underlying surface; in some cases, where lava flows into a standing water body, pillow structures develop with glassy rinds that can be extensively fractured, producing a pillow-palagonite complex with hyaloclastite textures. Permeability within flow tops and bottoms can be laterally highly variable over short distances due to depositional processes, but these zones are often transmissive on the regional scale (Burns et al., 2011). Due to the complexity of the connections within flow tops and bottoms, a given well may not encounter a groundwater flow zone that is open and connected to the aquifer. It has been noted that within areas of the CRBG, flow tops are more likely to form productive aquifers than flow bottoms (Lite and Grondin, 1988). The flow interiors can contain a variety of joints and fractures but lack the connectivity of the flow tops and bottoms. Flow interiors have low permeability and low storage characteristics, and they form effective confining units between permeable flow tops.

Four members of the Grande Ronde Formation are present in the study area: The Wapshilla Ridge member, the Ortley member, the Winter Water member and the Sentinel Bluff member. The Sentinel Bluff member is the youngest CRBG unit in the study area and its top is either eroded or severely weathered. The Sentinel Bluff member occurs only in the highest elevations of Dutch Canyon (Madin and Niewendorp, 2008) and no wells draw water from it. The hydrogeology of the other three units is described below. Some units have more than one important groundwater-flow zone.

2.3.3.1 Wapshilla Ridge Hydrostratigraphic Unit

The Wapshilla Ridge member is usually located at elevations between 200 and 300 meters to the west of the Portland Hills Fault and near sea level to the east of it. The bottom-most flow zone within the Grande Ronde Formation is at the contact between the upper sandstone unit of the Scappoose Formation and the base of the Wapshilla Ridge basalt. This contact is up to five meters thick (Ketrenos, 1986) and the flow zone is between three and nine meters thick according to well log records. This contact flow zone is found between 190 and 200 meters of elevation along the north ridge and 180 and 190 meters along the south ridge of Dutch Canyon. The upper Scappoose and the Wapshilla Ridge basalt were coeval with one another (Ketrenos, 1986) with Wapshilla Ridge lavas flowing over unconsolidated sediment creating large-scale soft sediment deformation structures between the two units. In some cases this resulted in plumes of Scappoose

Formation rocks in the basalt; in other areas palagonitic breccia is encapsulated within the arkosic upper Scappoose Formation. It is likely that this contact is a flow zone not only due to brecciated textures within the rocks but also because the basalt is juxtaposed against coarse-grained arkosic sandstone.

A second, small, flow zone within the Wapshilla Ridge member was noted in well log reports, this flow zone is mostly listed between two and ten meters thick and is only noted in a few well logs along the south rim of Dutch Canyon and in wells located on the east side of the Portland Hills Fault, making the lateral continuity of the zone difficult to determine.

Well yields for wells screened in the Wapshilla Ridge member ranged between 22 – 227 liters per minute. Transmissivity for the Wapshilla Ridge member was calculated for only one well, COLU_3018, screened within the lower flow zone, for which a drawdown value and a reliable well test was available. The transmissivity for this well was calculated as 2.6 m^2 d^{-1}, but no trend can be determined from a single value. Assuming an average thickness of 62 meters, an effective porosity of 10%, and an aquifer compressibility of 3.3×10^{-10} m^2/N (Table 2.1), storativity within the Wapshilla Ridge member was estimated to be 2.3×10^{-4} with an estimated specific storage of 3.7×10^{-6}.

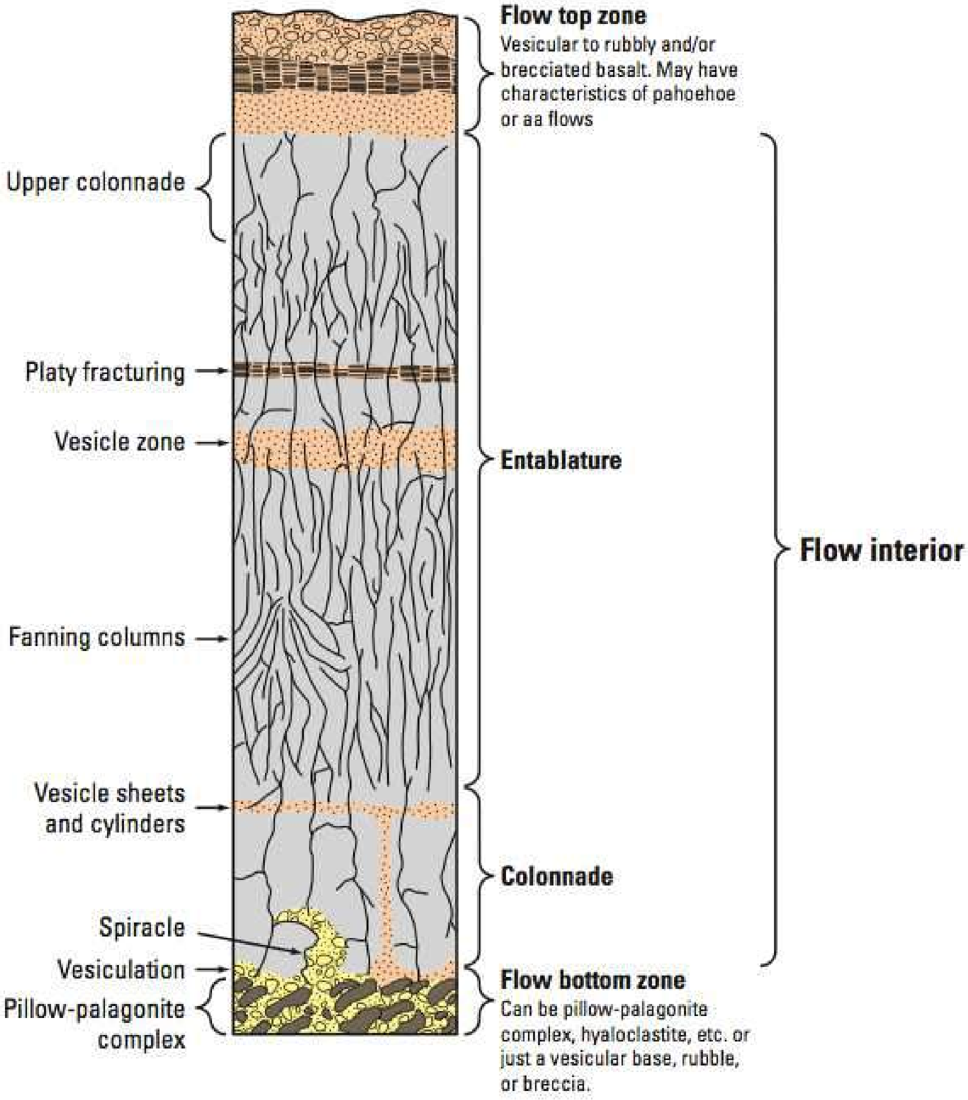


Figure 2.11. Geologic features that control flow and storage in Columbia River Basalts (from Reidel et al., 2003).

2.3.3.2 Ortley Hydrostratigraphic Unit

The next major flow zone exists at the contact between the Wapshilla Ridge member and the overlying Ortley member. As is the case with all Grande Ronde basalt units in the higher elevations of Dutch Canyon, there are few wells and fewer well logs that document this flow zone. Where noted, the contact between the Ortley and Wapshilla Ridge members is a discrete zone between two and three meters thick. More wells are located within the Ortley member at lower elevations east of the Portland Hills Fault near the main part of the city of Scappoose. In personal communication with property owners, these wells were often reported to have higher yields than those in the higher elevations, to the west across the fault line. In discussions with property owners who had wells drilled into the Ortley member, few owners reported productive yields west of the fault while most east of the fault had no problems drawing enough water from the Ortley. Most of the wells with yield information are located east of the Portland Hills Fault. Another flow zone is present within the Ortley member, likely along an individual flow top/bottom. In a groundwater study of Parrett Mountain (Broderson, 1995), 40 km south of Dutch Canyon, the Ortley member was found to be a relatively productive unit, although less so than the Wapshilla Ridge member. Assuming an average thickness of 62 meters, an effective porosity of 10%, and an aquifer compressibility of 3.3 x 10^{-10} m^2/N (Table 2.1), storativity within the Wapshilla Ridge member was estimated to be 2.3 x 10^{-4} with an estimated specific storage of 3.7 x 10^{-6}.

2.3.3.3 Winter Water Member

The contact between the Ortley member and the overlying Winter Water member is noted in two wells and is observed to be between 0.5 and 1.9 meters thick. The Winter Water member is only observed above 300 meters of elevation and only a few wells occurred above that elevation in the study area. Among those wells that are installed in the Winter Water member, a clay interbed is indicated just above an area of fractured basalt. The elevation of the well (485 m, well bottom at 419 m) suggests this is an interbed within the Winter Water member rather than the contact between the Winter Water and Ortley members. The unit is otherwise described as competent with some weathered zones.

2.3.4 Hydraulic Head Distribution

2.3.4.1 General Flow Regime

The distribution of hydraulic heads throughout the study area provides a picture of groundwater flow movement from higher to lower hydraulic head. In general, groundwater flows from the canyon ridges towards the valley floor, as expected. The elevation where first water is reported on well logs and static water elevations in Dutch Canyon both follow a similar trend, with high elevations in the west, decreasing towards the east (Fig. 2.12, 2.13). The highest elevations of first water trend strongly towards the east. The highest static water levels also trend to the east but display a stronger trend toward the Dutch Canyon valley floor than the first water elevations. It is assumed that the static water levels better represent the true distribution of hydraulic heads and hence the groundwater flow towards the localized discharge zones of the South Fork Scappoose Creek and towards the regional discharge zone trending toward the Columbia River.

The trace of the Portland Hills Fault can be deciphered from these elevations as groundwater elevations along with land surface elevation abruptly change by 10 - 20 meters between wells located within 100 meters of each other. This trend is a north-south lineament along the southeastern portion of the field area, becoming a northwestern trend north of the main valley floor. This observation matches the line of the Portland Hills Fault already mapped by Madin and Niewendorp (2008).

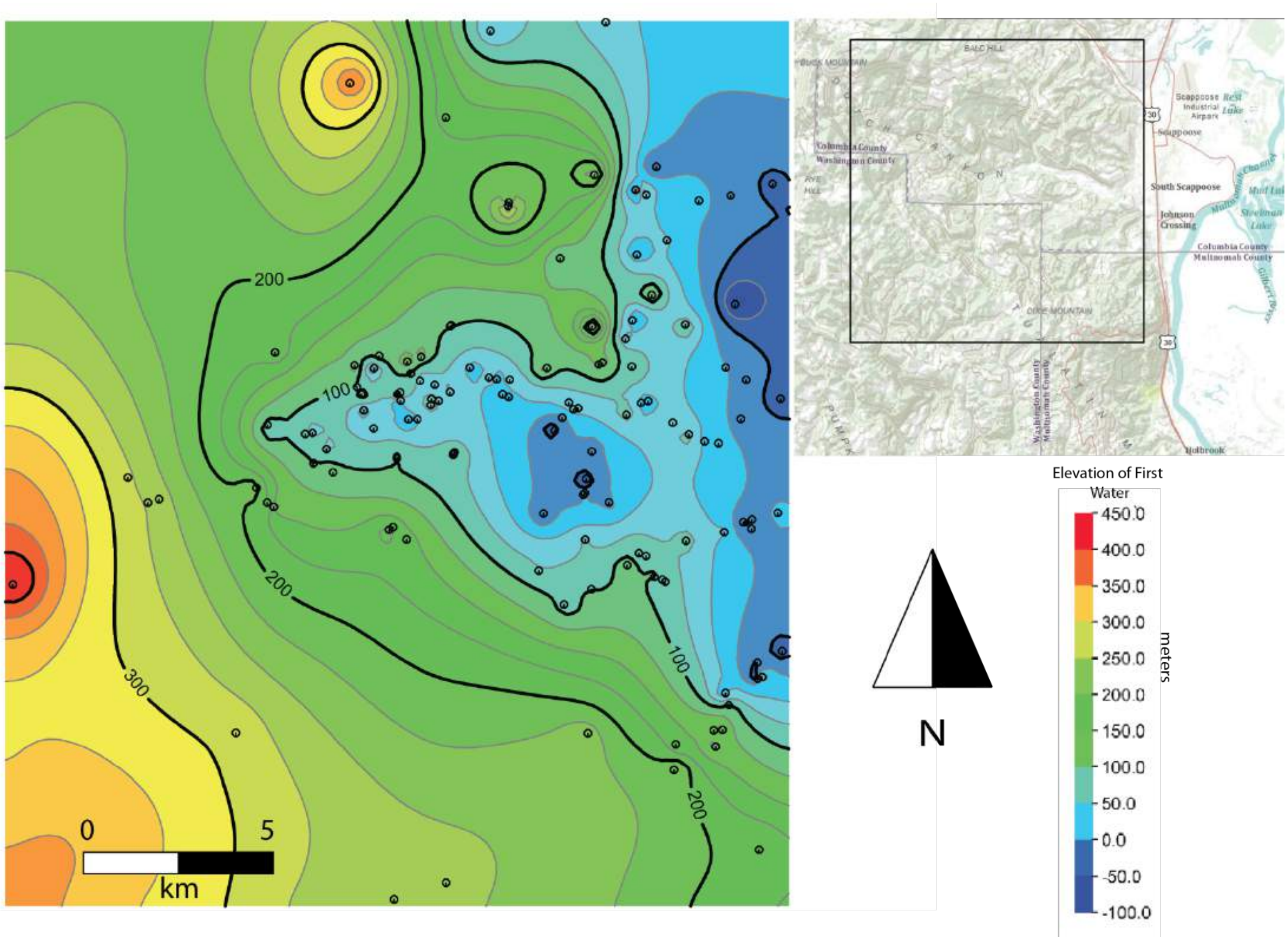


Figure 2.12. Contour map of the elevation of first water in wells in Dutch Canyon, as reported in individual well reports. Locations of wells from which data were obtained are represented by circular symbols

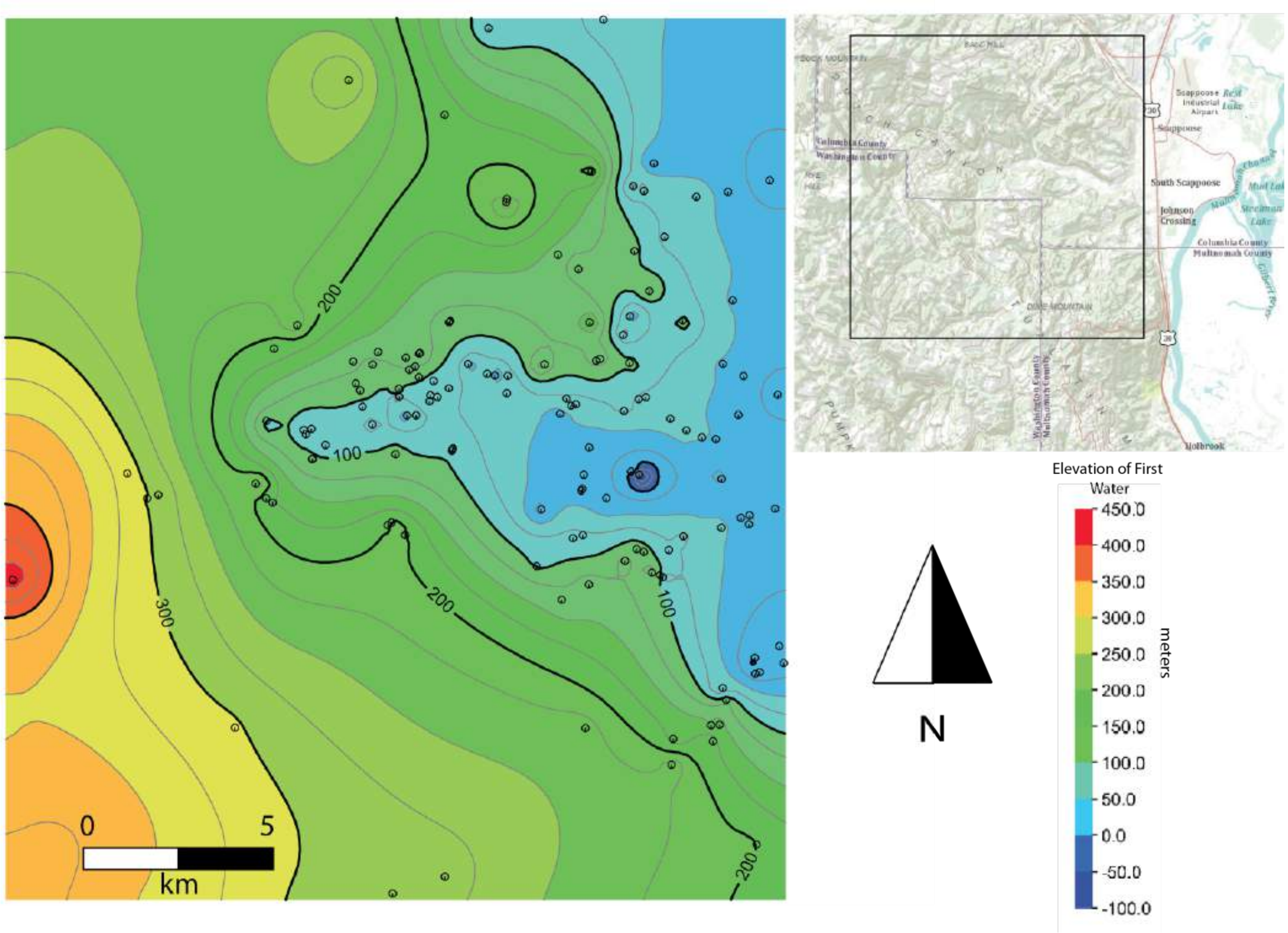


Figure 2.13. Contour map showing static water level elevations in Dutch Canyon. Locations of wells from which data were obtained are represented by circular symbols.

2.3.4.2 Relationship of Head Between Units

Determining hydraulic head values for Dutch Canyon comes with a degree of uncertainty. Water level values were recorded, in some cases, decades apart and may not reflect current values. Many well locations are not known with a high degree of certainty, potentially providing a large error for water elevations.

Transmissivities in all units are highly variable due primarily to the complexity and discontinuity of fracture systems in the basalt units and the overall heterogeneity of the Scappoose Formation. Additional aquifer compartmentalization may be the result of minor, discontinuous faults located west of the Portland Hills Faults, as mapped by Marty (1983). Faults often create hydrologic barriers within units. Given this and the range of transmissivity values calculated for individual hydrostratigraphic units within the study area, averaged values of transmissivity are likely of limited value in terms of reflecting the transmissivity of a given unit at any given location. However, the range of values estimated from the specific capacities provided in the well logs are generally $< 100\ m^2\ d^{-1}$ with the highest value being $370\ m^2\ d^{-1}$. Freeze and Cherry (1976) state that transmissivites greater than $1300\ m^2\ d^{-1}$ represent good aquifers for water well exploitation. By their definition, all of the aquifers in the study area would be considered poor to marginal at best in terms of groundwater production.

The CRBG units display a lateral discontinuity in Dutch Canyon, an example is on the northern rim of Dutch Canyon between wells COLU_3674 and COLU_3012, which is less than 1 km southeast and 60 meters lower in elevation. The static water elevation in COLU_3674, which is installed into the Ortley member, is 377 meters while

COLU_3012, installed to the interior of the upper hydrostratigraphic unit of the Scappoose Formation, contains a static water elevation of 155 meters. While it is expected for groundwater in different confined units to have different head values, the wells were both drilled through the same units and where COLU_3674 is productive in the Ortley, COLU_3012 did not record any groundwater in the Ortley, indicating the flowzone within the Ortley is not laterally continuous. This lateral discontinuity is potentially the result of faulting as it is near the location of a small fault and as Marty (1983) expressed, several small faults may be present west of the Portland Hills Fault, which could create hydrologic barriers.

Within the different hydrostratigraphic units of the Scappoose Formation, static water levels within the upper unit were often similar to one another. Head elevations within wells open in the middle and lower units that were near wells open to the upper unit were often much lower, indicating the middle and lower units may represent a disconnected system from the upper unit. This is represented in wells installed on and near Rabinsky Road. Wells installed to the upper unit (COLU_51176, COLU_3017, COLU_54, COLU_51353) have static water levels between 117 and 150 meters in elevation, decreasing toward the south. Wells installed to the middle and lower units (COLU_53311, COLU_52781, COLU_52251, COLU_50717, COLU_3159) in close proximity to the wells in the upper unit have static water level elevations between 25 and 56 meters, also trending to the south. The head elevations for all units appear to reflect the downward vertical gradient towards the Scappoose Creek discharge area, where a slight upward trend in head is observed at locations in the middle unit of the Scappoose

Formation near the creek at COLU_51056, COLU_52781, and COLU_50770 which have static water elevations between 60 and 70 m amsl. The change in vertical flow direction indicates that Scappoose Creek is a local discharge area.

Head elevations within the Scappoose Formation, especially the middle and lower hydrostratigraphic units, indicate that, while the units likely bear water throughout, there are many localized areas that do not yield useable quantities of groundwater. This variability is expected in areas with significant lateral heterogeneities and poorly sorted sands and silts. In some cases, the listed flow zones on the well reports are in areas of fractured rock. Localized fractures, in addition to lenses with different transmissivity values are a factor in locations of flow zones within the middle and lower hydrostratigraphic units. Even as most of the groundwater elevation readings were recorded over a long period of time, the common occurrence of wells in close proximity to one another that record high variability in groundwater within the same unit, compared to their neighbors suggest a high degree of lateral heterogeneity within the already low-yielding aquifers.

2.3.5 Area Hydrologic Parameters

Precipitation

The Scappoose Industrial Park weather station, at 25 meters elevation, recorded an average precipitation of 101 cm/year between 1999-2011, ranging between 75 cm in 2008 to 130 cm in 2010. A second, higher elevation, weather station was located in North Plains (ID# US10ORWS0025), 11 km southwest of the Scappoose Industrial Park weather station at an elevation of 440 meters. This station only contains data from

January 2008 to the present. The average annual precipitation for this station is 143 cm, ranging between 111 cm in 2009 to 178 cm in 2010. The South Fork Scappoose Creek watershed has an approximate surface area of 7,030 ha (17,370 acres, 70,293,900 m^2) (Bureau of Land Management, 2011). A very small percentage of Dutch Canyon is above 400 meters, but much of the area is above 200 meters elevation. It is assumed that 25% of the area receives annual precipitation similar to what the North Plains station receives and 75% of Dutch Canyon receives close to what the Scappoose Industrial Park receives; the resulting averaged precipitation value for Dutch Canyon is then 112 cm.

Baseflow Recession

The beginning of the 2009 baseflow recession (Fig. 2.14) for the East Fork Dairy Creek was determined to be on May 15 at 2.2 $m^3 s^{-1}$; discharge reached 10% of that value on September 26 and the baseflow recession ended on October 9 at 0.17 $m^3 s^{-1}$, after which there was a significant recharge event. The 2010 baseflow recession began on June 18 at 2.3 $m^3 s^{-1}$; 10% of that discharge was not reached prior to the end of the baseflow recession on October 14 when stream discharge was 0.3 $m^3 s^{-1}$.

The amount of recharge is equal to the total potential baseflow remaining at the end of the first baseflow recession subtracted from the volume of total potential groundwater discharge, V_{tp},for the beginning of the next recession. The amount of time for Q_0 to reach 0.1 Q_0 in 2009 was 135 days yielding a V_{tp} value of 1.1 x 10^7 m^3. The time for Q_0 to reach the end of the recession was 148 days yielding a potential baseflow, V_{148},value of 8.9 x 10^5 m^3. For the 2010 recession, the time between Q_0 and the end of the recession (0.1 Q_0 was not reached) was 119 days yielding a V_{tp} value of 1.0 x 10^7 m^3

(Fig. 2.14). The recharge value is equal to the total potential baseflow remaining at the end of the first baseflow recession subtracted from V_{tp} for the beginning of the next recession. Based on this calculation, the 2010 water year groundwater recharge in the East Fork Dairy Creek basin is estimated to have been 9.4 x 10^6 m^3. Dividing through by the area of the East Fork Dairy Creek basin (87,542,000 m^2) gives a per unit area recharge for the East Fork Dairy Creek basin of 0.11 m (11 cm). Assuming the same amount of recharge in the neighboring South Fork Scappoose Creek basin, a total of 7.7 x 10^6 m^3 can be estimated, which is 10% of the total precipitation. This is low percent for recharge which is likely due to the steep and forested topography which promotes runoff rather than recharge. Much of the upper areas of Dutch Canyon are mantled by low permeability loess which would also inhibit recharge. The hydrograph itself (Fig. 2.14) indicates this is a runoff-dominated system, as evidenced by the sharp vertical spikes in discharge resulting from precipitation events. This ratio of precipitation to recharge indicates that baseflow is not a major contributer to streams in Dutch Canyon but that does not mean that baseflow is unimportant to stream flow and stream levels. During summer months when precipitation is nearly nonexistent, the streams in Dutch Canyon are under baseflow conditions. The discharge during these months would likely be decreased from increased groundwater pumping.

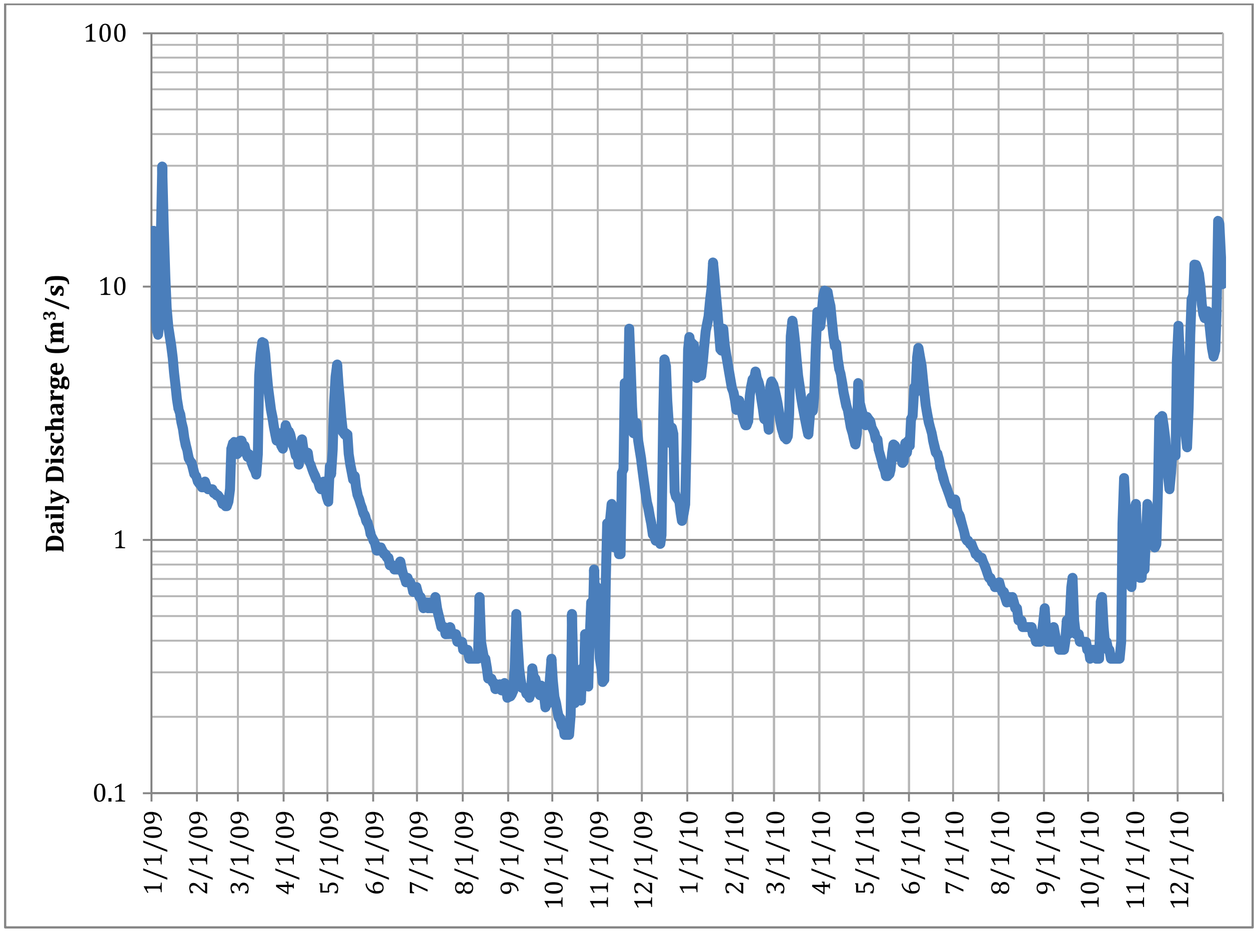


Figure 2.14: Semi-logarithmic stream hydrograph for East Fork Dairy Creek from January 2009 through December 2010 using daily mean stream discharge obtained from the USGS. Baseflow recession for 2009 season was from March 17 through October 9 and for 2010 season from April 3 through October 6.

2.4 Summary

The physical hydrogeology of the units in Dutch Canyon can be broadly defined as the difference between the basalt members of the Grande Ronde Basalt and the varying sedimentary layers within the Scappoose Formation. Both units, west of the Portland Hills Fault Zone, are generally characterized by varied, but generally limited transmissivities. To the east of the fault, wells are only constructed into the Wapshilla Ridge and Ortley members of the Grande Ronde Basalt.

The Grande Ronde Basalt in Dutch Canyon is located above 190 - 200 meters amsl, with the Wapshilla Ridge and Ortley members being the only CRBG units that provide information that can be extrapolated throughout the study area. Both the Wapshilla Ridge and Ortley members have multiple water-bearing zones, one each on the upper and lower contacts along with discrete local water-bearing zones within the basalt flow interior (Table 2.3). The zones are usually only a few meters thick, compared to the bulk flow interiors that can exceed 100 meters in thickness and are essentially aquitards. The well yields within the basalts aquifers are variable, but wells installed in the Wapshilla Ridge member typically have better yields than wells completed in the Ortley member or in the underlying units in the Scappoose Formation.

The basalt units also appear to vary in production from the east to the west side of the Portland Hills Fault. On the east size of the PHF, the Ortley member is the most prominent unit in outcrop and most wells are completed within it. It appears to produce at greater rates that of the units west of the PHF. That variance may not be significant as there are not many wells screened exclusively in the Ortley member west of the PHF and the well with the highest yield, COLU_50804, is on the contact between the Wapshilla Ridge and Ortley members, which is expected to be a more productive flow zone. To the west, the basalts are in the high elevation recharge area while the basalts east of the fault and within the discharge zone are in contact with the saturated Scappoose Formation.

The Scappoose Formation units are divided into four hydrostratigraphic units: the upper, middle, lower, and basal zone hydrostratigraphic units. No wells were installed to the basal zone, but it has been described in previous studies (Ketrenos, 1986; Van Atta and Kelty, 1985). The three Scappoose Formation units observed in this study have variable well yields and heterogeneous sediment layers but the arkosic upper unit is the most homogenous of the three units. Its contact with the overlying Wapshilla Ridge member is described as mingled by previous researchers as the two units are coeval with one another and the basalt flow caused some soft sediment deformation in the upper unit of the Scappoose Formation. The upper unit ranges in thickness between a few meters and nearly 100 meters thick and is located between 100 and 200 meters amsl on the west of the Portland Hills Fault. The middle unit of the Scappoose Formation lies below the upper unit, the contact is commonly defined by a thin and discontinuous layer of blue clay between the units. The middle unit is often described as blue to green and has few flow zones that yield more than 3 liters/min. Many of the well tests in the middle unit were able to pump between 30 - 50 liters/min but also noted large drawdown values over less than an hour indicating those numbers are likely not sustainable for frequent use. The middle unit is often laterally variable and has many lenses of clay and silt with the most permeable areas within the zone being fine-grained sandstone. The middle unit varies in thickness between 0 and 80 meters. The lower unit of the Scappoose Formation is the hydrogeologic basement of the study area, as no wells are installed through it. As the lower contact is never encountered in the study area, the thickness of the unit was not determined in this study, but extrapolating off existing stratigraphic thicknesses of the region, the unit is likely up to 100 meters thick. This unit is distinguished from the middle unit by containing less clay and silt and it is often described as being gray. Well and flow zone yields in this unit are similar to those in the middle unit.

Transmissivities in all units are variable (0.1 – 186 m^2 d^{-1}) due to the complexity and discontinuity of fracture systems in the basalt units and the overall heterogeneity of the Scappoose Formation. Despite the variability, the units typically have low transmissivities and no area within Dutch Canyon can be expected to have high transmissivity or good well production. Recharge was estimated at 10% of total precipitation, which is expected in an area with steep slopes, especially mantled with low permeability loess in the higher elevations, which promote runoff. While the recharge percent is not great, the streams in Dutch Canyon are likely under baseflow conditions during the summer months and could be impacted by increased withdrawals from the area which could also impact the groundwater levels if recharge could not keep up with the withdrawals..

CHAPTER 3. CHEMICAL HYDROGEOLOGY

3.1 Introduction

The geochemistry of groundwater in the study area is described in this section. Methods, including sample location selection and field sampling procedures are presented first, followed by results from analysis of field parameters, major ions, stable isotopes and arsenic. Ion activities and saturation indices for particular minerals are calculated and the results discussed in terms of geologic control by the different hydrostratigraphic units identified in Chapter 2 as well as general water quality. A discussion of potential impacts from a gas exploration well that has, for 70 years, been discharging highly saline connate waters due to artesian pressures is also included.

3.2 Methods

3.2.1 Sampling Locations

Forty-eight samples of well, spring, and stream water were collected from throughout Dutch Canyon in August and September of 2010 and August of 2011. Additional field quality control / quality assurance (QA/QC) samples were also collected. Site location data for the 2010 and 2011 sampling rounds are presented in Table 3.1.

Prior to the initial round of sampling, a mailer was sent out from Columbia Soil and Water Conservation District asking residents if they would be willing to participate in an academic study of the groundwater. Initially, those residents who positively responded were contacted to arrange sampling of their water wells. Other wells were targeted based on geography or well screen elevations in an attempt to provide reasonable coverage of the study area. This also provided a reasonable minimum number of samples from each major water-bearing unit in order to have a basis of comparison in regards to water qualities in each.

Prior to each day's field sampling, well reports for sites scheduled or targeted to be sampled were obtained from the Well Log Query site on the Oregon Water Resources Department website. When the proper well report was in question, the property owner was asked about previous owners or shown the well reports for the area to discern which was on their property. In several cases, the property owner had a copy of their well report on hand. Additional sampling sites were identified via referrals from friends and neighbors or by simply knocking on the doors of residents who appeared to be home at the time. In these latter cases, well log information was not known prior to sampling, except if the correct well report was already printed out and identified by the property owner. As a result of this, well reports for several sampled wells were never located.

Table 3.1: Sample IDs and locations for water samples collected from Dutch Canyon, Scappoose, OR, 2010-2011.

OWRD Well Log ID	Sample Date	UTM Easting (m)	UTM Northing (m)	Ground Elev. (masl)*	Well Bottom Elev. (masl)**	Hydrostratigraphic Unit
COLU_29	9/8/10	507336	5065879	124	31	Scappoose Lower Unit
COLU_3012	8/18/11	504673	5069463	313	96	Wapshilla Ridge/Scappoose Upper Unit Contact
COLU_3030	8/18/11	507089	5067383	224	68	Scappoose Middle Unit
COLU_3040	8/26/11	506254	5067638.9	282	86	Scappoose Lower Unit
COLU_3116	8/26/10	507535	5065740	104	34	Scappoose Middle Unit
COLU_3155	8/24/11	504588	5066136	93	28	Scappoose Middle/Lower Mix
COLU_3158	8/24/2011	503993	5065764	68	21	Scappoose Middle Unit
COLU_3159	8/24/11	504497	5066086	111	34	Scappoose Middle Unit
COLU_3163	8/24/10	503823	5065810	68	42	Scappoose Lower Unit
COLU_3166	8/26/10	503017	5065744	89	61	Scappoose Middle Unit
COLU_3167	8/23/10	503041	5065695	85	-1264	Basement
COLU_3174	9/9/10	506801	5064204	181	87	Scappoose Middle Unit (LS)
COLU_3176	9/9/10	507024	5064310	154	62	Scappoose Middle Unit (LS)
COLU_3186	8/16/11	508260	5064636	68	24	Ortley/Wapshilla Mixed

Table 3.1 (continued): Sample IDs and locations for water samples collected from Dutch Canyon, Scappoose, OR, 2010-2011.

OWRD Well Log ID	Sample Date	UTM Easting (m)	UTM Northing (m)	Ground Elev. (masl)*	Well Bottom Elev. (masl)**	Hydrostratigraphic Unit
COLU_3203	8/12/11	508570	5064820	70	21	Ortley/Wapshilla Ridge
COLU_322	8/25/10	502488	5065115	258	201	Wapshilla Ridge
COLU_3674	8/16/11	503544	5069872	430	131	Ortley/Wapshilla Mixed
COLU_50330	8/30/10	506012	5067811	313	-4	Scappoose Lower Unit
COLU_50634	8/26/11	506284	5065032	79	24	Scappoose Middle Unit
COLU_50898	8/30/10	508165	5064711	78	-7	Scappoose Lower Unit
COLU_51056	8/23/10	503041	5065695	85	72	Scappoose Lower Unit
COLU_51176	8/25/11	504383	5066652	168	51	Scappoose Upper Unit
COLU_51353	8/24/10	504218	5066597	161	137	Scappoose Upper Unit
COLU_51947	8/26/10	507707	5065658	96	2	Scappoose Middle Unit
COLU_51948	8/26/11	506462	5066562	155	47	Scappoose Middle Unit
COLU_52049	9/9/10	506937	5064344	152	54	Scappoose Middle Unit (LS)
COLU_52245	8/25/11	508136	5065923	65	20	Scappoose Lower Unit
COLU_52773, COLU_52774	8/24/10	503599	5066553	136	16	Scappoose Middle/Lower Mix

Table 3.1 (continued): Sample IDs and locations for water samples collected from Dutch Canyon, Scappoose, OR, 2010-2011.

OWRD Well Log ID	Sample Date	UTM Easting (m)	UTM Northing (m)	Ground Elev. (masl)*	Well Bottom Elev. (masl)**	Hydrostratigraphic Unit
COLU_53408	8/25/10	505410	5066179	67	42	Scappoose Lower Unit
COLU_53503	9/9/10	506056	5063741	198	76	Wapshilla Ridge (LS)
COLU_53628	8/26/10	507939	5065169	23	12	Alluvial Deposits
COLU_53868	8/16/11	502649	5064892	192	58	Scappoose Middle Unit
COLU_53912	8/26/10	501170	5064941	351	266	Scappoose Lower Unit
COLU_54	8/24/10	593680	5066212	126	100	Scappoose Upper Unit
COLU_541	8/24/10	503628	5066295	135	97	Scappoose Middle Unit
COLU_549	8/30/10	507936	5064595	78	40	Scappoose Middle Unit
COLU_93	9/8/10	505402	5068431	309	225	Wapshilla Ridge
COLU_993	9/9/10	507490	5064493	110	70	Scappoose Middle Unit (LS)
Creek	8/23/10	502316	5066211	103	103	Stream
Spring	8/24/10	503750	5065070	141	141	Scappoose Upper Unit
Spring	8/23/10	502246	5066200	115	115	Scappoose Upper Unit
Spring	8/23/10	502517	5065823	103	103	Scappoose Upper Unit

Table 3.1 (continued): Sample IDs and locations for water samples collected from Dutch Canyon, Scappoose, OR, 2010-2011.

OWRD Well Log ID	Sample Date	UTM Easting (m)	UTM Northing (m)	Ground Elev. (masl)*	Well Bottom Elev. (masl)**	Hydrostratigraphic Unit
Unknown	8/30/10	508260	5065363	34	--	Scappoose Fluvial Deposits
Unknown	9/9/10	508052	5065388	50	--	Scappoose Lower Unit
WASH 8355	8/24/11	504004	5064624	227	69	Scappoose Upper Unit

W=well, SP=spring, ST=stream, SW=salt (gas) well*Ground elevation from USGS National Elevation Dataset (NED), 1/9 arc-second digital elevation model (vertical accuracy (+/- ~3 m), using onsite GPS-based UTM locations. **Well bottom elevation calculated as measured ground elevation – depth of well as determined from OWRD well log. Elevation for springs assumed to be ground level. Well reports for E51 & E64 have not been

3.2.2 Well Sampling

Over half of the residential wells sampled had a filtration system for their well water and many others had a water softener. Any water sample collected after filtration and water softening would not be chemically representative of the groundwater so precautions were taken to ensure water samples were collected in line before filters or water softener units. In most cases, in line spigots situated "upstream" of filtration or softener units were available for sampling. In cases where multiple spigots were available, the closest spigot to the wellhead was used for sample collection to minimize purging times. Water samples were collected by attaching a hose equipped with a flow-through cell to the spigots.

3.2.2.1 Purging

To ensure that samples collected were representative of natural formation waters, each well was purged of stagnant water present in the well casing and associated piping that may have undergone chemical changes. Purged water was diverted onto the ground some distance (~5 - 8 meters) from the well casing. Because wells recharge with water at different rates, the pumping rate and purging method had to be adjusted to avoid conditions such as aeration in the well which could change the ground water characteristics or damage the pump.

To calculate the volume of water needed to purge a given well, the well radius, well depth, and depth to recorded static water level were determined from the water well log. With this information, the height of the water column (B) was calculated by subtracting the depth to water from the well depth. Well volume was then calculated using this water column height and the well casing radius. Once purging began, the rate of flow was calculated by timing the filling of a plastic container. A long-standing protocol is to purge three well volumes from a well prior to sampling. However, pumping rates varied between 4 - 15 liters per minute with well volumes ranging between 200 - 2,000 liters, making purging of three well volumes difficult in many cases with limited available time. All wells sampled were either domestic or irrigation wells, and were assumed, and often verified, as daily use wells such that well water was purged on a daily basis. Therefore, wells were purged until metered readings of pH, specific conductivity and temperature were stable over three measurements collected at least two minutes apart. In one case (COLU_3166), purging was not possible because the well was located in the owner's basement. A sample was taken with the assumption that the well was fully purged via the owner's daily use; the owner verified that the well had been in use throughout the morning immediately prior to sampling.

3.2.2.3 Measuring Field Parameters

Groundwater quality parameters were measured in the field with a YSI Professional Plus multiparameter meter inserted into a flow-through cell to eliminate exposure of the groundwater to the atmosphere. Specific measurements included water temperature (°C), pH, specific conductivity (μS/cm), dissolved oxygen (in % and mg/L), and the oxidation-reduction potential (ORP) (mV). The meter was calibrated for all parameters according to the manufacturer's recommendations. Calibration for pH was conducted prior to sampling each well using a three-point calibration with pH 4, 7, and 10 buffers. Dissolved oxygen was calibrated regularly by inserting the probe (following a 10-minute warmup of meter) into a water-saturated atmosphere representing 100% saturation. Calibration for specific conductivity and ORP was performed prior to the first sample of each day, and as needed after that. A standard solution of 1412 µS/cm was used to calibrate the specific conductivity probe. Fresh Zobel solution, stored away from sunlight to minimize photo-degradation, was used to calibrate the ORP probe (Ag/AgCl electrode, 4 M KCl) to provide measurements relative to the standard hydrogen electrode (Eh, in mv). The ORP reading was converted to Eh by adding the reference electrode potential (200 mV at 25°C) to the field measurement to bring the reading in line with measurement against a standard hydrogen electrode. Prior to using any solution, and between solutions, distilled water was used to clean the probe, the cups used to hold calibration solutions and the flow-through cell. GPS coordinates, elevation, weather conditions and barometric pressure were also recorded at each well location.

3.2.2.4 Water Well Sampling

Samples were collected as soon as the readings on the multiparameter meter were stable over three consecutive readings collected at least two minutes apart. At each location, samples for major cations and anions, arsenic and stable hydrogen and oxygen isotopes were taken. Samples were collected in pre-labeled 60-ml or 125-ml low-density polyethylene (LDPE) bottles that had been soaked for a minimum of 24 hours in 5% nitric acid and thoroughly rinsed with 18 megohm-cm (nanopure) water. Samples were field-filtered through 0.45 micron polysulfone filters, either using a Whatman 50-mm-diameter in-line filter attached to the flow-through cell outlet tube or, in cases where these filters readily plugged, one or more Whatman 25-mm-diameter syringe filters. Cation and arsenic samples were acidified to < 2 pH with 10 drops of concentrated nitric acid (HNO_3). Anion and isotopes samples were collected by overfilling bottles before capping to minimize headspace in the sample bottles. Sample bottles were placed in zip lock bags, with each location separate from one another. The bagged sample bottles were put in a cooler with ice or icepacks immediately after sampling for transport to the lab. All ion and trace element samples were maintained at ~4ºC until laboratory analyses were performed.

During sampling, the appearance (odor, turbidity, etc.) of the water was noted. Field analysis of total water alkalinity was performed at each site using a Hach digital titrator. For this procedure, 100 mL of water was measured into a 250 mL glass beaker. Then, four drops of bromocresol green solution was added to the water. A pre-loaded cartridge containing either 0.16 or 1.6 N sulfuric acid (H_2SO_4) was added to the titrator, and the acid was slowly added to the solution, which was constantly mixed with a swirling motion. When the solution would turn from green to clear, the amount added would be recorded and total alkalinity as mg/L $CaCO_3$ was calculated according to the manufacturer's instruction.

3.2.3 Spring Sampling

Springs were sampled using two procedures. If the spring was not directly accessible but fed into a system that supplied a house, and was accessible at a spigot, sampling procedures were identical to well sampling, without calculation of purging. Sampling still did not occur until meter readings became stable to ensure evacuation of stored water in associated piping. If the spring was directly accessible, a grab sample was taken by inserting a syringe into the outlet, filling it with water, attaching a .45 micron filter, and filling the collection bottles from the syringe. The YSI multimeter probe was inserted into the water afterwards to obtain field parameter readings. Other aspects of sampling were identical to well sampling procedures.

3.2.4 Stream Sampling

As with accessible springs, stream grab samples were collected by inserting a syringe into the stream, filling it with water, attaching a .45 micron filter, and filling the collection bottles from the syringe. The YSI multimeter probe was inserted directly into the stream to measure field parameters.

3.2.5 Quality Assurance / Quality Control Samples

A blank sample was taken for every 15 water samples for quality control. This sample was taken in the field, using the same equipment as with normal water samples. Distilled water was run through a length of field-rinsed poly tubing and through the flow-through cell, field filtered and bottled and preserved as per regular samples. Due to an oversight, a field blank was not collected for sampling during August 2011. A replicate sample was also taken for every 15 sites. The replicate sample was taken directly after collecting the initial sample following the same procedures but with a new filter.

3.2.6 Chemical Analyses

3.2.6.1 Major Ion Analysis

All water samples were analyzed for major ions in the Trace Element Analytical Laboratory housed in the Department of Geology at Portland State University. Major cations were analyzed with either a Perkin Elmer Analyst 300 atomic absorption spectrometer (AAS) or an Agilent Model 720 inductively coupled plasma optical emission spectrometer (ICP-OES). Major anions were analyzed using a Dionex Model 2500 ion chromatograph. Silica analysis was performed using the molybdate-yellow colorimetric method, measuring absorption with a Beckman Coulter DU 730 ultraviolet visible (UV-Vis) spectrophotometer. A set of three to eight external standards prepared from certified commercial stock solutions were used to calibrate the instruments prior to each sample batch. Samples were diluted to bring analyte concentrations under the highest standard if the initial concentration exceeded that standard by >10%.

3.2.6.2 Arsenic Analysis

Samples for arsenic analysis were collected at each location. Scappoose did not have a history of elevated arsenic levels within Dutch Canyon, but elevated arsenic levels have been detected in pisolitic bauxite deposits developed on CRBG units in adjacent areas (Fassio, 1990) and concerns about the potential for elevated groundwater arsenic concentrations were expressed by Columbia County officials. Arsenic samples were collected in 125-mL bottles and acidified with nitric acid. These samples were kept cool until hand delivered to Test America in Beaverton, Oregon for analysis. Samples were analyzed for arsenic by Test America using inductively coupled plasma – mass spectrometry following the EPA 200 Series Method.

3.2.6.3 Stable Isotope Analysis

Additional samples were collected at each location and sent to the Colorado Plateau Isotope Laboratory (CPIL) at Northern Arizona University for stable oxygen and hydrogen isotope analysis. Stable isotopes can help delineate waters recharged from different elevations and under different climate regimes and, hence, may be of use in delineating water in different units as well as older meteoric or connate waters potentially trapped in the older marine sediments. Isotopic sample preparation was by the water-CO_2 equilibration method (Epstein and Mayeda, 1953) for oxygen isotopes, and by the zinc reduction method for deuterium (Coleman et al., 1982). Samples sent to CPIL were analyzed on a Thermo Finnigan DeltaPLUS XL IRMS using a Gas Bench II gas preparation and introduction system. Isotopic values are reported in the standard δ-notation as per mil (‰) deviations from the VSMOW (Vienna Standard Mean Ocean Water) reference standard. Analytical precision is ±0.1‰ and ±1.0‰ for oxygen and deuterium, respectively.

3.2.7 Geochemical Modeling

3.2.7.1 Ion Activities

Dissolved ions in a solution influence one another through the electrostatic forces so the total concentration of the dissolved ions does not accurately measure their reactivity (van der Perk, 2006). Due to this, the activity of the ions is used to calculate chemical reactions in aqueous solutions. Chemical activity is related to molar concentration via:

$$[x_i] = \gamma_i m_i \tag{3.1}$$

where χ_i equals the activity of ion i, γ_i equals the activity coefficient, and m_i is the molal concentrationof the ion i. The activity coefficient depends on the ionic strength of the solution, temperature, and the valence of the ion in question. An activity coefficient can be estimated by use of the extended Debye-Hückel equation:

$$log\ \gamma_i = \frac{-Az_i^2\sqrt{I}}{1+B\alpha_i\sqrt{I}} \tag{3.2}$$

where *A* and *B* are temperature dependent constants, I is the ionic strength, and α_i is the radius of the hydrated ion. This equation can be used to calculate values of the activity coefficient up to an ionic strength (I) of 0.1, or around 4,000 mg/L total dissolved solids (Domineco and Schwartz, 2000). For the waters collected in Dutch Canyon, activities were calculated using the geochemical modeling program Visual MINTEQ. The chemical concentrations determined for each well, spring, or stream sampled was entered along with temperature, pH, and Eh.

3.2.7.2 Determination of Saturation Indices

Equilibrium calculations are used to establish if groundwater is in equilibrium with respect to one or more minerals. Groundwater may be under-saturated, saturated, or over- saturated with respect to various minerals. Groundwater that is under-saturated with respect to a particular mineral would tend to dissolve that mineral until the dissolution reaction reached equilibrium; groundwater that is over-saturated with respect to a given mineral would tend to precipitate that mineral. However, such mineral dissolution and precipitation reactions are often limited by kinetic constraints, such that few groundwaters are in equilibrium with all (or even many) of the minerals with which they are in contact. Nonetheless, minerals which are determined to be in equilibrium with waters often control aqueous ion concentrations and, potentially, pH and redox conditions as well.

The ratio of the ion activity product (IAP) to the solubility product or mineral equilibrium constant (Ksp) is used to determine the state of equilibrium or disequilibrium The generalized equation for the ion activity product is:

$$IAP = \frac{[Y]^y[Z]^z}{[C]^c[D]^d} \tag{3.3}$$

where [Y], [Z], [C], and [D] are known activities in an actual aqueous sample. If the IAP is equal to the equilibrium constant (unit ratio), the water is assumed to be in equilibrium with the given mineral. If IAP/K is less than one, the groundwater is under-saturated for the given mineral, and if it is over one, it is supersaturated. The saturation index (SI) is often used to express the saturation state of a mineral in groundwater and is expressed as:

$$\mathrm{SI} = \log\left(\frac{IAP}{K}\right) \tag{3.4}$$

A mineral in equilibrium will have an SI of zero, if it is undersaturated the SI will be negative and if oversaturated the SI will be positive. For the samples collected in Dutch Canyon, Visual MINTEQ was used to calculate the saturation index for all minerals in the associated database using the calculated ion activities.

3.3 Results

3.3.1 Quality Assurance and Quality Control Results

Quality assurance and quality control were accounted for by various means. Field blanks were used to quantify concentrations of any analytes introduced via field procedures. Similarly, laboratory blanks were used to quantify background concentrations of analytes introduced via laboratory equipment or background contamination. Field and laboratory replicates were used to determine overall reproducibility and analytical precision. Verification standards and matrix spike samples were used to verify accuracy for different analytical methods.

For sampling in 2010 (Table 3.2), two field blanks were collected. No analytes were detected above method reporting limits in the first field blank. Analysis of the second field blank yielded 2.38 mg/L of Na, 0.23 mg/L of K, and 0.1 mg/L of Ca. The measured concentrations of K and Ca in the second blank are near method reporting limits and do not represent significant contamination. The sodium level is significant, though small, and may be due to inadequate rinsing of field equipment following sampling of some very saline wells installed in the Scappoose Formation. No other cations or anions were detected above method reporting limits in this blank sample. Due to an oversight, a field blank was not collected for sampling during August 2011.

Two field duplicates (two sets of replicates) were collected in 2010 and one in August 2011 to determine overall reproducibility – combining real variations in sampled water, variations resulting from field procedures or contamination, and analytical variations - for each analyte. The precision goal for this project was set at +/- 25% determined as relative percent difference (RPD):

$$\text{RPD (\%)} = (\text{Concentration 1} - \text{Concentration 2}) / \text{Average Concentration} \quad (3.5)$$

The RPD is only applicable when both concentrations are five times the reporting limit. RPD values for all analytes are provided in Table 3.2. RPDs for all cations, F, and alkalinity were < 5%; RPDs for Cl and SO_4^{2-} ranged from 3 and 2% - 22 and 24%, respectively. A RPD of 42.7% was determined for arsenic in one replicate set; however, in this case the arsenic concentrations were below the method reporting limit, although still detectable. At these very low (sub-part-per-billion) levels, even small differences result in high percentage differences and the RPD threshold does not apply. Laboratory duplicates were also analyzed with a precision goal of +/-15% RPD in concentrations. For the laboratory duplicates, As, F, and NO_3 had RPD values over 15%; however, all of these analytes had concentrations that were not greater than 5 times the reporting limit. All samples where RPD was appropriate (where concentrations were > 5x the reporting limit) were within the 15% range. The stable isotope samples were checked against two

Table 3.2: Quality Assurance/Quality Control Results (ND = no detect)

Analysis	Field Blank (2) Concentrations (mg/L)	Field Duplicates (3) RPDs (%)	Laboratory Duplicate RPD (%) Range (n)	Laboratory Spike Sample % Recovery Range
Target /Threshold:	**ND**	**+/- 25%**	**+/- 25%**	**+/- 20%**
As(total)	ND (n=1)	42.7%* (n=1)	9.25-23%*	107-109.6%
Na	ND, 2.38	0.03, 1.47, 2.99%	4.1% (1)	98-114%
K	ND, 0.23	0.08, 0.1, 2.61%	0.11% (1)	84-110%
Ca	ND, 0.1	0.02, 1.18, 0.79%	1.17-1.77%	84-105%
Mg	ND, ND	0.12, 0.57, 1.23%	0.49% (1)	85-104%
Fe	ND, ND	0.4, 0.69, 0.00%	9.23% (1)	94-100%
Cl	ND, ND	3.38, 13.9, 21.2%	0.17-16.1%	101-106%
SO_4	ND,ND	2.17, 13, 24.3%	0.18-7.96%	101-108%
F	ND,ND	0.16%, 7.7%, ND	0.1-43.3%*	97-103%
Br	ND,ND	ND, ND, 10.8%	1.2% (n=1)	96% (n=1)
NO_3	ND,ND	ND, ND, ND	0.97-53.6%*	98-129%
HPO_4	ND,ND	ND, ND, 13%	10.2% (n=1)	97-107%
Field Alk**	-- --	0.62% (n=1)	--	--

RPD for duplicates only applicable when both concentrations > 5x reporting limit. For cases marked with *, one or both concentrations were below this threshold. In the case of arsenic, both field and laboratory duplicate sample contained < 0.00034 mg/L, which is below the method reporting limit (0.001 mg/L), though above method detection limit (0.00019 mg/L). **Field alkalinity (mg/L as CaCO3) was used to calculate bicarbonate values (HCO3-).

sets of three normalization standards and secondary check standards, seven drift standards, and three blank samples. The values in these standards were averaged and compared to expected results. All stable isotope standards were within 1% of the expected value with standard deviation values between 0.11 and 0.57.

The charge balance error may be considered a gross measure of total analytical errors. Charge balance errors were calculated via:

$$C.B.E.(\%) = \frac{\left(\Sigma m_{cations} - \Sigma m_{anions}\right)}{\left(\Sigma m_{cations} + \Sigma m_{anions}\right)} \text{ x } 100 \qquad (3.6)$$

The target threshold for CBE is ±20%. The range of CBE's (Table 3.2) was -18.8 to +32.6% with an average of 3.0%. Charge balance errors of two samples , COLU_3167 (gas well), CBE = 25%, and COLU_3030, CBE = 32.6%, exceeded the threshold level. Analytical errors for the gas well sample were likely high due to the levels of dilution required (5,000 – 10,000x). Degassing of sample was also visible in the field. The COLU_3030 sample did not require dilution.

Matrix spike samples were passed through the lab equipment where a known concentration of a target analyte is placed into a sample. Check standards, samples of known concentration in a clean matrix, were also used to ensure accuracy.

3.3.2 Field Parameters

Variability in groundwater temperature showed some difference between the basalt units on either side of the Portland Hills Fault and between the basalt units and the sedimentary units. The groundwater temperature in the basalt aquifers is somewhat higher than in the Scappoose Formation but is not significantly different from that in the sedimentary aquifer units.

The pH of groundwater varied between 6.02 - 9.3 (Table 3.3). While there was no correlation between dissolved oxygen levels and groundwater pH, there did appear to be stratigraphic and geographic trends. Higher pH values were often associated with the upper unit of the Scappoose Formation while the lower pH values were typical of the lower and middle units of the Scappoose Formation, particularly in wells installed in the lower elevations on the northern flank of Dutch Canyon. Many wells with low pH values in the middle and lower units of the Scappoose Formation have groundwater in equilibrium with iron-bearing minerals like siderite. The upper unit of the Scappoose Formation displays other chemical differences when compared to the lower and middle units, as discussed below.

The specific conductivities of groundwaters, a proxy measure for total dissolved solids, ranged from <40 to a maximum of 43,600 uS/cm in the abandoned gas exploration well (at site COLU_3167), with a high of 1,810 uS/cm in the relevant water-bearing units at site COLU_3163. Specific conductivity showed the strongest relation between stratigraphic units and geographic areas of all the field parameters. All groundwater with a specific conductivity value of 400 uS/cm or greater came from either the middle or lower unit of the Scappoose Formation. Within these units, specific conductivity had significant variability with values being grouped geographically, both in location and elevation, with some variability within the flow units, which will be discussed later.

As reducing environments will have low to zero levels of oxygen, dissolved oxygen (D.O.) and reduction potential values (Eh) were highly correlated. Both D.O. and Eh values displayed a greater geographic trend than a stratigraphic trend, with all formations containing some waters with strongly positive Eh values and higher relative D.O. readings and others with negative Eh and low D.O. The middle and lower units of the Scappoose Formation were the most likely aquifers to contain low-redox waters. However, the low-redox waters also appear to be controlled by proximity to recharge and discharge areas within the sedimentary aquifer indicating the area close to the discharge zone coming from more local recharge areas are less likely to be low-redox waters than the deep regional waters.

Table 3.3: Field water quality parameters of groundwater in Dutch Canyon. Samples collected August-September 2010 & August 2011. Temperature, EC, DO, pH, and Eh were measured in situ with a YSI multiparameter probe

Sample	Hydrogeologic Flow Unit	Sample Date	pH	Eh (mV)	Electrical conductivity (uS/cm)	Total Dissolved Solids (mg/L)	Temp. (°C)	O_2 (mg/L)
A24-SP-0824	Scappoose Upper Zone	8/24/10	6.09	523	82	48	12.6	9.57
B10-W-0819	Scappoose Middle Zone	8/19/11	6.36	299.7	95	64	14.4	1.1
COLU_29	Scappoose Lower Zone	9/8/10	7.28	59	299	220	12.8	0.33
COLU_3012	Scappoose Upper Zone	8/18/11	6.88	309	56	37	11.6	4.81
COLU_3030	Scappoose Middle Zone	8/18/11	6.74	345.2	148	99	12.4	9.08
COLU_3040	Scappoose Lower Zone	8/26/11	9.3	-44	764	511	13.1	0.04
COLU_3116	Scappoose Middle Zone	8/26/10	7.65	72	351	237	12.3	0.04
COLU_3155	Scappoose Lower Zone	8/24/11	7.03	161.4	320	214	11.4	0.21
COLU_3158	Scappoose Middle Zone	8/24/11	7.17	55	646	432	13.8	0.07
COLU_3159	Scappoose Middle Zone	8/24/11	6.78	170	304	203	13.3	0.12
COLU_3163	Scappoose Lower Zone	8/24/10	8.33	112	1814	1453	13.2	1.4
COLU_3166	Scappoose Middle Zone	8/26/10	6.86	747	687	330	12.7	0.2

Table 3.3 (continued): Field water quality parameters of groundwater in Dutch Canyon. Samples collected August-September 2010 & August 2011. Temperature, EC, DO, pH, and Eh were measured in situ with a YSI multiparameter probe

Sample	Hydrogeologic Flow Unit	Sample Date	pH	Eh (mV)	Electrical conductivity (uS/cm)	Total Dissolved Solids (mg/L)	Temp. (^oC)	O_2 (mg/L)
COLU_3167	"Basement"	8/23/10	7.91	52.7	43634	16822	19	0.3
COLU_3174	Scappoose Middle Zone (LS)	9/10/10	6.93	291	385	249	12.5	1.79
COLU_3176	Scappoose Middle Zone (LS)	9/10/10	7.68	272	379	237	13.8	1.96
COLU_3186	Wapshilla Ridge	8/16/11	7.52	42	348	233	13.2	0.05
COLU_3189	Scappoose Upper Zone (LS)	9/10/10	6.09	405	118	86	12.4	7.2
COLU_3203	Ortley	8/12/11	7.37	75	317	212	13.2	0.1
COLU_322	Wapshilla Ridge	8/25/10	6.19	346	87	52	12.3	8.1
COLU_3674	Ortley	8/16/11	7.11	387	184	123	14.2	9.9
COLU_50330	Scappoose Lower Zone	8/30/10	7.09	326	150	106	12.7	9.25
COLU_50634	Scappoose Middle Zone	8/26/11	8.63	-48	1115	746	13.6	0.05
COLU_50898	Scappoose Lower Zone	8/30/10	6.99	107	245	170	11.5	0.05
COLU_51056	Scappoose Lower Zone	8/23/10	6.02	631	1163	462	14.1	3.1

Table 3.3 (continued): Field water quality parameters of groundwater in Dutch Canyon. Samples collected August-September 2010 & August 2011. Temperature, EC, DO, pH, and Eh were measured in situ with a YSI multiparameter probe

Sample	Hydrogeologic Flow Unit	Sample Date	pH	Eh (mV)	Electrical conductivity (uS/cm)	Total Dissolved Solids (mg/L)	Temp. (^{o}C)	O_2 (mg/L)
COLU_51176	Scappoose Upper Zone	8/25/11	7.76	347.4	286	191	15.9	2.97
COLU_51353	Scappoose Upper Zone	8/26/10	6.5	191	195	122	13.9	0.09
COLU_51947	Scappoose Middle Zone	8/26/10	7	325	314	165	16.3	4.8
COLU_51948	Scappoose Middle Zone	8/26/11	7.46	302	303	203	16	3.6
COLU_52049	Scappoose Middle Zone (LS)	9/10/10	6.98	255	297	203	13.1	7.05
COLU_52245	Scappoose Lower Zone	8/25/11	7.84	66	352	236	14.6	0.11
COLU_52774	Scappoose Lower Zone	8/24/10	8.54	293	528	280	18.2	3.8
COLU_53408	Scappoose Lower Zone	8/25/10	8.44	43	470	327	12.4	0.11
COLU_53503	Wapshilla Ridge (LS)	9/10/10	7.09	97	463	280	12.5	0.06

Table 3.3 (continued): Field water quality parameters of groundwater in Dutch Canyon. Samples collected August-September 2010 & August 2011. Temperature, EC, DO, pH, and Eh were measured in situ with a YSI multiparameter probe

Sample	Hydrogeologic Flow Unit	Sample Date	pH	Eh (mV)	Electrical conductivity (uS/cm)	Total Dissolved Solids (mg/L)	Temp. (^{o}C)	O_2 (mg/L)
COLU_53628	Alluvial Sediment	8/26/10	7.4	54	451	267	12.4	0.32
COLU_53868	Scappoose Middle Zone	8/16/11	8.7	279	338	226	13.3	1.5
COLU_53912	Wapshilla Ridge	8/26/10	6.92	142	166	134	10	0.06
COLU_54	Scappoose Upper Zone	8/24/10	6.3	169	147	110	12.2	0.1
COLU_541	Scappoose Middle Zone	8/24/10	6.79	99	153	116	11.8	0.05
COLU_549	Scappoose Middle Zone (LS)	8/30/10	6.65	309	108	98	13	6.4
COLU_93	Wapshilla Ridge	9/8/10	6.39	375	111	51	10.8	9.62
COLU_993	Scappoose Middle Zone (LS)	9/10/10	7.87	362	373	233	14.2	7.77
DUTCHCANYONSTREAM	Stream	8/12/11	7.96	239.8	180	120	14.4	9.5
E51-W-0830	Scappoose Fluvial Deposits	8/30/10	7.4	38	364	233	12.5	0.34
E64-W-0908	Scappoose Lower Zone	9/8/10	7.29	231	323	183	12.1	0.92

Table 3.3 (continued): Field water quality parameters of groundwater in Dutch Canyon. Samples collected August-September 2010 & August 2011. Temperature, EC, DO, pH, and Eh were measured in situ with a YSI multiparameter probe

Sample	Hydrogeologic Flow Unit	Sample Date	pH	Eh (mV)	Electrical conductivity (uS/cm)	Total Dissolved Solids (mg/L)	Temp. (°C)	O_2 (mg/L)
J-SP-0823	Scappoose Upper SS	8/23/10	7.22	280	152	95	12.6	10.63
J-ST-0823	Stream	8/23/10	7.6	285	73	40	12.4	10.68
S-SP-0823	Scappoose Upper SS	8/23/10	7.13	304.1	372	220	14.4	7.91
SALTCREEKUPPER	Stream	8/18/11	14.1	261.3	64	43	14.1	9.95
SFSCAPPOOSECK	Stream	8/12/11	7.84	254.7	110	74	15.3	9.7
WASH_8355	Scappoose Upper Zone	8/24/11	6.93	331	234	157	12.9	2.27

LS = well located in mapped landslide area, BDL = below detection limit, NM = not measured

3.3.3 Analytical Chemistry

Field water quality parameters for all samples are provided in Tables 3.3. Elemental concentrations are provided in Table 3.4. Isotope data are provided in Table 3.5 and arsenic data are provided in Table 3.6. The chemistries of waters associated with each hydrostratigraphic unit are examined in the sections that follow. The hydrogeochemistries including major ion chemistry of the various units are further compared in the discussion (Section 3.4).

3.3.3.1 Stable Isotope Results

Deuterium (D) and ^{18}O are isotopes of hydrogen and oxygen that are heavier than the more common H and ^{16}O atoms. As water changes phase, isotopic fractionation occurs where heavier isotopes will be more abundant in the condensed phase. Water that evaporates from the ocean contains a lower percentage of D and ^{18}O than the ocean as evaporation preferentially takes up the lighter isotopes. Similarly, precipitation will be enriched in the heavier isotopes in comparison to the air mass it is coming from as the heavier isotopes are preferentially incorporated into condensate.

The controlling factors on the amount of D and ^{18}O in the precipitation of an area are latitude, temperature, elevation, and position within a landmass relative to the oceanic source of precipitation. These effects describe the principle that as air cools, the fractionation between phases is increased and that as an air mass moves over a land mass, it becomes depleted in D and ^{18}O in comparison to sea water as precipitation depletes the air mass and evaporation from surface waters will also be depleted in D and ^{18}O.

Testing for D and ^{18}O can aid in differentiating between aquifer units. Isotopes can be used to identify groundwaters recharged at significantly different elevations and to discern meteoric water that was recharged during a different climatic regime (e.g., 100s to 1000s of years ago), or, if the units are of low permeability, connate groundwater (Bradbury and Taylor, 1984; Hendry and Wassenaar, 1999).

A total of 52 samples were analyzed for ^{2}H and ^{18}O concentrations in Dutch Canyon and are reported as delta values (‰) relative to Vienna Standard Mean Ocean Water (VSMOW) (Table 3.5 and Fig. 3.1). Values for the gas well COLU_3167 (-7.81 ‰ $\delta^{2}H$ and -31.84 ‰ $\delta^{18}O$) are not included in Figure 3.1 as they are so different from shallow groundwaters that the scale of the figure would be significantly altered. Measured isotopic variations for all samples excluding COLU_3167 range from -69.5 to -85.3‰ for δ2H and -9.97 to -11.85‰ for δ18O.

Regression of measured $\delta^{2}H$ vs $\delta^{18}O$ values show that samples plot on a line ($\delta^{2}H = 5.2\ \delta^{18}O – 17.5$), which has a lower slope than the Global Meteoric Water Line (GMWL) defined as $\delta^{2}H = 8\delta^{18}O + 10$ by Craig (1961) (Fig. 3.1). This slope is near the low end of non-evaporative water lines; generally, area waters will plot with a greater slope (Kendall and Coplen, 2001). A slope of 5.2 would normally suggest evaporative conditions (Ingraham and Taylor, 1989) which would be unlikely in this area of the Pacific Northwest. As some groundwater is in a local groundwater path while other wells appear to draw water from a deeper, regional, groundwater path, it is possible that the slope is lowered due to some of the samples having come from water that has exchanged with rock minerals for a long period of time, potentially even containing a contribution of diluted connate waters from fine-grained units within the Scappoose Formation.

Most stable isotope samples plotted near one another along the regional trend line, usually without much difference between units. The one outlier in the figure is from COLU_3040, which has been identified as chemically different from the surrounding wells in chemical analysis, possibly withdrawing water from a part of a deeper regional flow system compared to more local or intermediate flow systems in much of Dutch Canyon.

Oxygen isotope values were compared with Cl^- concentration and specific conductivity to discern if a trend indicating water-rock interaction could be determined (Fig. 3.2, 3.3). Elevated levels of specific conductivity were associated with more negative O^{18} values, a trend which was also observed to a lesser degree with Cl^-. The samples with elevated levels of these variables were located in the discharge areas of the Middle and Lower Scappoose Formation where groundwater residence times and the degree of water-rock interaction is greatest.

Table 3.4: Elemental concentrations (mg/L or ppm) in water samples from Dutch Canyon, Aug-Spt, 2010 & 2011. Blank cells indicate element concentration below detection limit.

Sample	Flow Unit	Na^+	Mg^{2+}	Ca^{2+}	K^+	HCO_3^-	SO_4^{2-}	Cl^-	Si_{total}	Fe_{total}	NO_3^-	F^-	HPO_4^{2-}	CBE (%)
Method Reporting Limits:	N/A	0.15	0.15	0.2	0.15	1	0.18	0.15	1	0.15	0.45	0.15	0.6	
A24-SP-0824	S. U.	6.2	2.08	6.36	1.3	24	0.28	7.19	6.1		0.96	0.26		13.1
B10-W-0819	S. M.	7.61	1.36	4.49	0.97	12	4.32	8.32	27.56	0.13	0.14	0.08		13.7
COLU_29	S. L.	20.7	7.39	20.4	3.02	143	8	2.55	12.1	2.6		0.14		0.5
COLU_3012	S.U.	4.52	1.93	4.94	1.03	50	0.54	2.68	42.19	0.05		0.06	0.13	-18.1
COLU_3030	S. M.	7.81	4.61	11.1	3.11	37	1.08	2.32	63.98	0	0.06	0.14	0.6	32.6
COLU_3040	S. L.	115.8	0.23	1.86	1.94	347	6.49	28.16	25.83	0.03	0.32	0.37	0.81	-11.9
COLU_3116	S. M.		8.23	26.1	3.61	165	12.27	2.75	9.6	0.31		0.31		-18.8
COLU_3155	S. L.	54.93	--	0.05	0.53	121	6.38	6.75	76.64	0.01		0.17	0.9	2.2
COLU_3158	S. M.	66.62	4.99	23.69	5.52	138	0.11	61.85	39.73			0.31	0.48	7.2
COLU_3159	S. M.	31.08	3.4	15.77	4.24	123	0.88	13.02	77.62	0.45		0.17	0.83	2.5
COLU_3163	S. L.	471	2.29	19.8	9.3	193	0.56	700	1.1	0.05		0.28		-2.3
COLU_3166	S. M.	62	9.56	40.8	5.61	90	9.14	143	15.3					-0.4
COLU_3167	"Basement"	7670	32.7	1670	54	5		8848	5.2	2.01			1.01	25.5
COLU_3174	S. M. (LS)	62			0.41	131	8.6	30.1	11.9			0.15	1.34	-7.8
COLU_3176	S. M. (LS)	67	1.54	2.4	4.28	153	6.17	1.54	11.7	0.05		0.07		10.1
COLU_3186	W. R.	8.94	12.66	30.58	2.42	146	3.64	2.84	61.71	1.66		0.19	0.09	8.3
COLU_3189	S. U. (LS)	8.52	2.95	6.25	2.12	63	0.85	1.41	9.6		0.12	0.06		-5.7
COLU_3203	Ortley	10.03	11.07	29.88	2.25	137	7.21	1.71	70.71	0.33		0.21	0.08	8.6
COLU_322	W. R.	7.52	2.68	4.48	1.88	32	1.23	2.38	8.4			0.24		14.4
COLU_3674	Ortley	4 .33	3.67	8.24	1.41	63	0.64	1.94	49.83		0.31	0.09	0.4	-8.3
COLU_50330	S. L.	9.42	3.73	8.83	2.87	76	1.55	2.24	8.5		0.79	0.09		-4.1

Table 3.4 (continued): Elemental concentrations (mg/L or ppm) in water samples from Dutch Canyon, Aug-Spt, 2010 & 2011.

Sample	Flow Unit	Na^+	Mg^{2+}	Ca^{2+}	K^+	HCO_3^-	SO_4^{2-}	Cl^-	Si_{total}	Fe_{total}	NO_3^-	F^-	HPO_4^{2-}	CBE (%)
COLU_50634	S. M.	167.6	0.21	1.88	2.49	336	4.42	116.8	23.15	0.1	0.4	0.36	2.23	-8.7
COLU_50898	S. L.	13.5	8.36	14.2	1.81	79	2.93	1.23	16.9	5.3		0.13		18.5
COLU_51056	S. L.	155	9.52	43.7	5.36	39	8.55	257	4.8	0.17	0.13	0.23		9.9
COLU_51176	S. U.	8.49	11.84	37.15	3.32	123	17.35	2.54	50.41	0.04	0.09	0.48	0.54	14.5
COLU_51353	S. U.	14.1	3.8	10.3	3.47	73	9.25	2.13	18.2	3.06		0.31		2.6
COLU_51947	S. M.	15.7	9.25	22.4	3.7	105	9.27	1.91	16.3			0.32		14.9
COLU_51948	S. M.	10.38	6.79	34.62	4.22	116	9.52	2.75	53.54	0		0.18	0.49	13.4
COLU_52049	S. M. (LS)	12	8.05	20.6	3.04	139	15.3	2.18	15.9	0.9		0.13		-7.5
COLU_52245	S. L.	32.88	4.03	20.97	3.99	209	0.73	2.69	39.62	0.23	0.3	0.3	0.21	-9.3
COLU_52774	S. L.	97	1.22	7.4	3.85	100	14.7	108.8				0.19	0.71	-2.3
COLU_53408	S. L.	107	0.31	1.37	3.02	206	1.16	5.77	11			0.21		15
COLU_53503	W. R. (LS)	10.8	10.1	43.8	3.53	159	49.9	2.26		6.84		0.09		-1.7
COLU_53628	Alluvial	21.4	13.04	31.9	3.09	148	0.12	41.6	11.9	8.7		0.34		1.1
COLU_53868	S. M.	48.69	0.53	4.44	3.23	179	14.26	1.87	25.95	0	0.17	0.11	0.34	-14.3
COLU_53912	W. R.	9.22	4.8	9.31	3.31	99	5.09	1.73	14	2.6		0.3		-13.8
COLU_54	S. U.	9.36	4.42	11	2.51	66	7.99	4.32	14.5	6.56		0.29		0.6
COLU_541	S. M.	13.1	3.96	9.9	3.14	73	6.4	2.39	16.1	5.34		0.34		2.4
COLU_549	S. M. (LS)	13.6	6.09	9.21	1.74	63	1.88	2.15	13.1	0.05		0.33		16.7
COLU_93	W. R.	6.34	3.04	2.5	1.66	34	1.2	1.68	11.6			0.08		4.6
COLU_993	S. M. (LS)	40	7.68	22.9	4.92	139	16.6	1.51	6.1		0.39	0.06		15.4
DUTCH CANYON STREAM	Stream	9.83	4.22	15.24	2.51	82	9.26	5.39	40.95	0.03	0.38	0.08	0.3	-2.6

Table 3.4 (continued): Elemental concentrations (mg/L or ppm) in water samples from Dutch Canyon, Aug-Spt, 2010 & 2011.

Sample	Flow Unit	Na^+	Mg^{2+}	Ca^{2+}	K^+	HCO_3^-	SO_4^{2-}	Cl^-	Si_{total}	Fe_{total}	NO_3^-	F^-	HPO_4^{2-}	CBE (%)
E51-W-0830	Fluvial	21.8	9.57	19.1	2.45	150	3.57	17.5	4.1	11.2		0.34		-4.8
E64-W-0908	S. L.	12.5	8.51	28.3	4.01	126	0.82	2.09	10.6			0.2		12.7
J-SP-0823	S. U.	7.05	4.28	12.8	1.65	62	4.47	1.77	11.9		1.49	0.06	0.64	7.1
J-ST-0823	Stream	4.76	1.29	2	1.18	27	1.76	2.73	4.9					-11.1
S-SP-0823	S. U.	46	5.17	15.6	3.24	100	17.3	45.7	6.5		0.38	0.08		0
SALT CREEK UPPER	Stream	6.85	2.59	7.7	1.64	45	0.78	2.13	24.87	0.04	0.15	0.05	0.08	6.9
SF SCAPPOOSE CK	Stream	3.55	1.78	4.53	0.61	16	1.97	7.1	31.21	0.4	0.19	0.05	0.11	4
WASH_8355	S. U.	9.52	4.78	24.97	4.3	111	7.63	2.3	37.08	0		0.11	0.45	2.9

CBE = charge balance error LS = well located in landslide area, W. R. = Wapshilla Ridge, S. U. = Scappoose upper unit, S. M. = Scappoose middle unit, S. L. = Scappoose lower unit

Table 3.5: Isotopic composition of groundwater in Dutch Canyon.

Site	Hydrogeologic Flow Unit	d^{18}O(‰)	dD(‰)
COLU_3012	Ortley/Wapshilla Mixed	-10.61	-71.97
COLU_3674	Scappoose Upper Contact	-10.6	-72.8
COLU_3030	Scappoose Middle SS	-10.43	-72.41
WASH_8355	Scappoose Upper SS	-10.74	-72.74
COLU_52245	Scappoose Lower Zone	-10.73	-74.23
COLU_541	Scappoose Middle Zone	-10.14	-71.18
COLU_54	Scappoose Upper Zone	-10.2	-71
COLU_3163	Scappoose Lower Zone	-10.65	-74.95
A24-SP-0824	Scappoose Upper Zone	-9.98	-69.85
COLU_51353	Scappoose Upper Zone	-10.17	-72.31
COLU_51176	Scappoose Upper Zone	-10.08	-72.2
COLU_51056	Scappoose Middle Zone	-10.39	-69.94
COLU_3158	Scappoose Lower Zone	-10.25	-71.64
COLU_52774	Scappoose Middle Zone	-10.42	-72.5
B10-W-0819	Scappoose Lower Zone	-10.01	-68.91
COLU_53408	Scappoose Middle Zone	-10.18	-73.84
COLU_3159	Scappoose Lower Zone	-10.37	-72.58
COLU_3155	Scappoose Middle Zone	-10.29	-72.42
COLU_3155	Scappoose Middle Zone	-10.46	-72.42
COLU_51948	Scappoose Middle Zone	-10.58	-72.77
COLU_50634	Scappoose Middle Zone	-11.09	-77.93
COLU_3189	Scappoose Upper Zone (LS)	-10.08	-71.57
COLU_3176	Scappoose Middle Zone (LS)	-10.42	-73.39
COLU_3174	Scappoose Middle Zone (LS)	-10.72	-72.45

Table 3.5: Isotopic composition of groundwater in Dutch Canyon.

Site	Hydrogeologic Flow Unit	$d^{18}O$(‰)	dD(‰)
COLU_993	Scappoose Middle Zone (LS)	-10.95	-74.28
COLU_52049	Scappoose Middle Zone (LS)	-10.69	-72.8
COLU_53503	Wapshilla Ridge (LS)	-10.8	-72.9
DUTCHCANYONSTREAM	Stream	-10.12	-69.52
COLU_29	Scappoose Lower Zone	-11.03	-73.79
COLU_53628	Alluvial Sediment	-10.18	-71.49
COLU_50898	Scappoose Middle Zone (LS)	-10.3	-71.78
COLU_549	Scappoose Lower Zone	-10.53	-72.66
E51-W-0830	Scappoose Fluvial Deposits	-9.97	-70.64
COLU_3203	Ortley/Wapshilla Ridge	-10.38	-71.31
COLU_3186	Ortley/Wapshilla Mixed	-10.39	-71.42
COLU_51947	Scappoose Middle Zone	-10.93	-72.2
COLU_3116	Scappoose Middle Zone	-11.28	-73.76
E64-W-0908	Scappoose Lower Zone	-10.55	-72.17
COLU_3040	Wapshilla Ridge	-11.85	-84.28
COLU_53912	Scappoose Lower Zone	-11	-73.39
COLU_50330	Scappoose Lower Zone	-10.66	-72.85
J-Sp-0823	Scappoose Upper SS	-10.36	-70.13
J-ST-0823	Stream	-10.32	-70.62
COLU_93	Wapshilla Ridge	-10.57	-73.15
S-SP-0823	Scappoose Upper SS	-10.49	-71.23
SALTCREAKUPPER	Stream	-10.26	-69.5
SFSCAPPOSECK	Stream	-10.49	-69.5
SHR-SP-0825	Winter Water Spring	-10.24	-69.07
COLU_3166	Scappoose Middle Zone	-10.42	-70.85

Table 3.5: Isotopic composition of groundwater in Dutch Canyon.

Site	Hydrogeologic Flow Unit	$d^{18}O$(‰)	dD(‰)
COLU_322	Wapshilla Ridge	-10.73	-72.93
COLU_53868	Scappoose Middle Zone	-10.74	-74.11

LS = well located in landslide topography
Note: Delta (d) values in ‰ = ($R_{sample}/R_{standard}$ - 1) x 1000
where "R" is the ratio of the heavy to light isotope ($^{2}H/^{1}H$ or $^{18}O/^{16}O$)
in the sample or standard (Vienna Standard Mean Ocean Water).

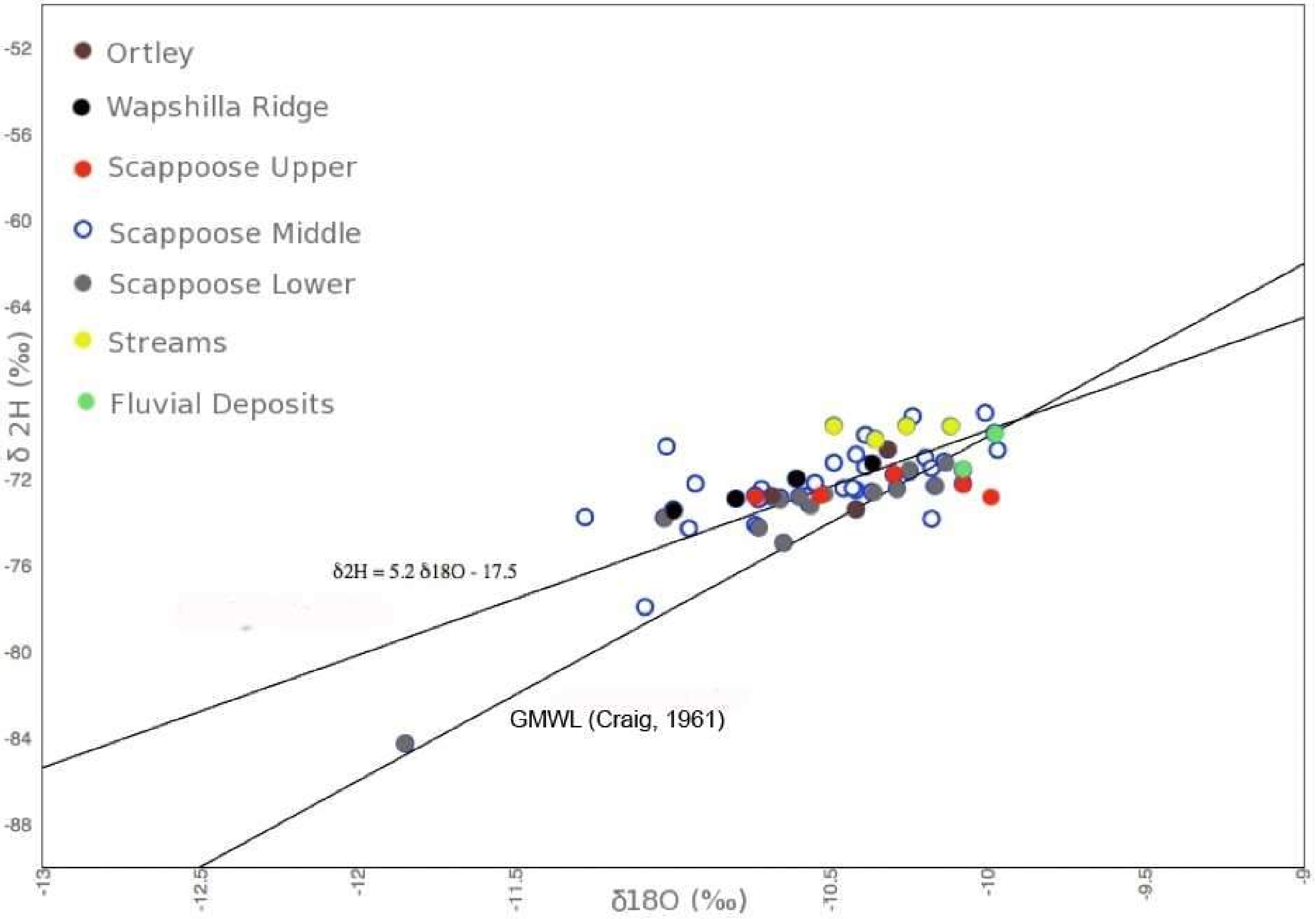


Figure 3.1: δ2H and δ18O delta values for all samples. Data from this study plot on a line given by δ2H = 5.2 δ18O – 17.5. The Global Meteoric Water Line (GMWL) defined as δ2H = 8 δ18O + 10 by Craig (1961) is shown.

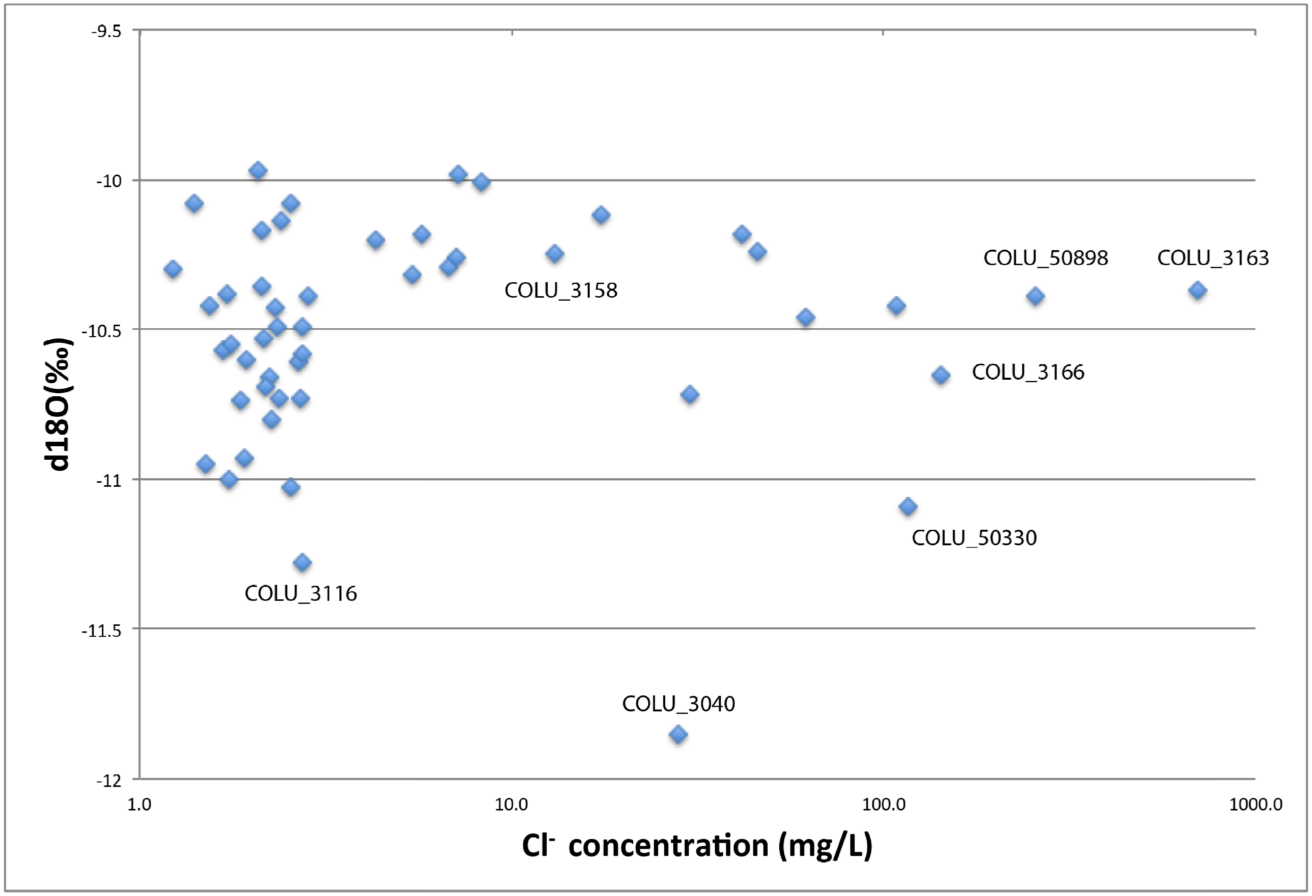


Figure 3.2: O^{18} isotope values plotted against Cl^- concentration. While low Cl^- values are present through a range of O^{18} values, high concentrations are most prevalent between -11.2 and -10.4 d18 $^0/_{00}$.

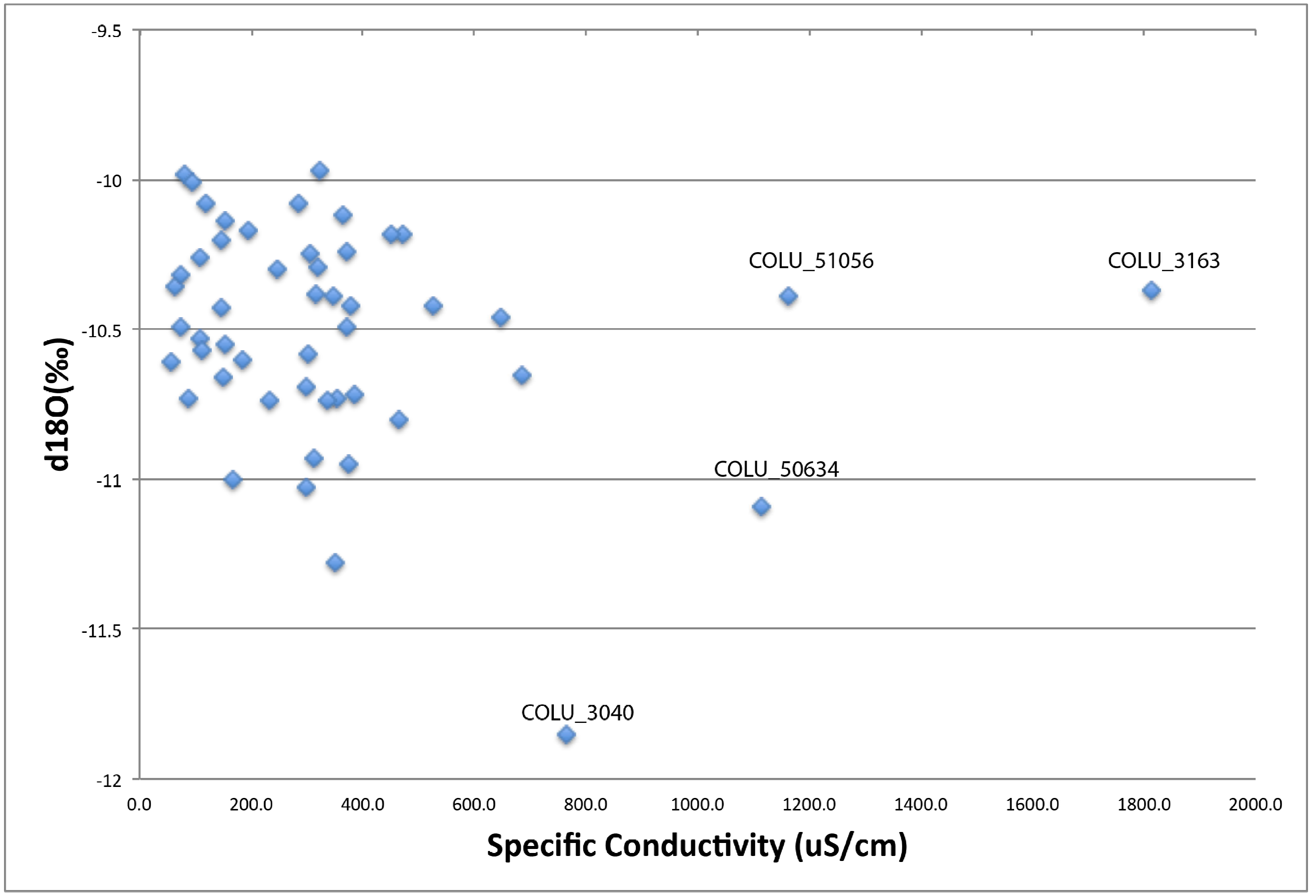


Figure 3.3: O^{18} isotope values plotted against specific conductivity. There is a slight trend for high levels of conductivity in groundwater with more negative O^{18} values.

3.3.3.2 Arsenic and Nitrate

The drinking water standard in the United States for arsenic is 10 μg/L. Although there is no historical record of arsenic in the water in Dutch Canyon, arsenic has been associated with lateritic bauxite deposits, which have been noted in the weathered basalt ridges in Columbia County (Marty, 1983). Long-term arsenic exposure from drinking water can cause cancer and skin lesions. It has also been associated with developmental effects, cardiovascular disease, neurotoxicity and diabetes (Gunduz et al., 2010).

The drinking water standard for nitrate in the United States is 10 mg/L. Nitrate in groundwater does not often occur naturally at those levels meaning that increased nitrate levels are typically the result of contamination, often agricultural. The major risk of high levels of nitrate in groundwater is to pregnant women and infants below six months who could develop blue baby syndrome, a potentially fatal disease.

Of all samples collected, only one, COLU_52777, was found to contain arsenic concentrations above drinking water standards, 15.3 μg/L (Table 3.5) and none over 10 mg/L nitrate. The arsenic positive well is located in the fluvial sediment along South Fork Scappoose Creek near the mouth of Dutch Canyon and the well is only used for irrigation. The domestic water source for the well is also very shallow (8.5 meters) in comparison to most drinking water wells in the area. The property the well is located on is connected to the city of Scappoose's water and residents are in no danger from the arsenic in their irrigation well. A possible source of the arsenic in this water is from past pesticide use in the farming areas nearby as lead arsenic was commonly used in pesticides until it was banned in 1988 (Ayuso et al., 2010).

3.4 Discussion of Results

3.4.1 Chemical Differences Between Units

3.4.1.1 Sentinel Bluffs and Winter Water members, Grande Ronde Basalt

The Sentinel Bluffs and Winter Water members of the Grande Ronde Basalt are present in elevations above 300 meters in Dutch Canyon, and some residential wells in the area draw water from the Winter Water member. However, no wells opened in these units were sampled during either field session because of the relatively few number of wells and the fact that none of the associated property owners contacted regarding sampling were available.

Table 3.6: Arsenic concentration in groundwater in Dutch Canyon from samples collected in 2010 and 2011 field seasons. No domestic well contained arsenic above the drinking water standard of 10 μg/L (0.01 mg/L). One irrigation well, E44, did.

Sample	As_{total} (mg/L)
Method Reporting Limits:	0.001
COLU_541	0.003
COLU_54	0.001
COLU_3163	ND
A24-SP-0824	ND
COLU_51353	0.001
COLU_3167	0.005
COLU_51056	ND
COLU_52774	0.001
COLU_53408	ND
COLU_3189	ND
COLU_3176	ND
COLU_3174	ND
COLU_993	ND
COLU_52049	ND
COLU_53503	0.001
COLU_29	ND
COLU_53628	0.015
COLU_50898	ND
COLU_549	0.001
E51-W-0830	0.009
COLU_51947	ND
COLU_3116	ND
E64-W-0908	0.001
COLU_53912	0.004
COLU_50330	ND
J-SP-0823	0.002
J-St-0823	ND
COLU_93	ND
S-SP-0823	0.003
SHR-SP-0825	ND
COLU_3166	ND
COLU_322	ND
COLU_3158	ND
COLU_3155	ND
WASH_8355	0.001

Table 3.6: Arsenic concentration in groundwater in Dutch Canyon from samples collected in 2010 and 2011 field seasons. No domestic well contained arsenic above the drinking water standard of 10 μg/L (0.01 mg/L). One irrigation well, E44, did.

Sample	As_{total} (mg/L)
COLU_50634	ND
COLU_3012	ND
COLU_3203	ND
COLU_51948	ND
COLU_51176	ND
COLU_52245	ND
B10-W-0819	ND
COLU_3155	ND
COLU_3186	ND
COLU_53868	ND
COLU_3030	ND
COLU_3674	ND
COLU_3040	ND
COLU_3159	ND

Italicized values < MRL, but above MDL.
ND indicates element concentration below detection limit in sample.

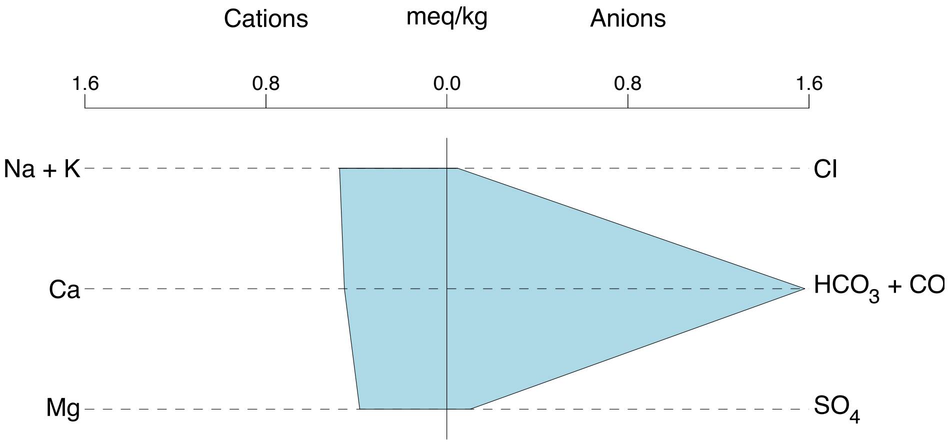
3.4.1.2. Ortley member, Grande Ronde Basalt

Wells drawing water from the Ortley member were located in two regions within Dutch Canyon, at elevations above 300 meters west of the Portland Hills Fault, and near sea level east of the Portland Hills Fault. There were few available wells in these areas as the higher elevations in Dutch Canyon have few residents and the area east of the Portland Hills Fault is largely served by the City of Scappoose public water system. As a result of these limitations, only three of the wells sampled were positively identified as being opened to the Ortley member: well COLU_3674, located on the northern rim; and wells COLU_3186 and COLU_3203, both located on Callahan Road east of the PHF.

These wells appear to be open to flow zones along the contact between the Ortley and the underlying Wapshilla Ridge members.

Water chemistry in the Ortley member appears to vary with location, although with only three sample locations, additional well sampling in the areas would help in confirming spatial differences. Water temperature ranged from 13.2 - 14.2 °C, pH from 7.11 - 7.37, Eh from 42 - 387 mV, and specific conductivity from 184 - 348 uS/cm (Table 3.3). Two of the samples, COLU_3186 and COLU_3203, which were collected from wells installed east of the Portland Hills Fault were found to be reducing and contained nearly twice the amount of total dissolved solids as the well west of the fault located on the northern ridge. Plotting stable isotope results for the Ortley member groundwater displays a similar trend to other units, clustered around the local trend line.

In COLU_ 3186 and COLU_3203 the wells east of the Portland Hills Fault, iron concentrations were 1.66 mg/L and 0.33 mg/L and groundwater was in or close to equilibrium (SI 0.29 & -0.58) with siderite ($FeCO_3$), which may be controlling iron concentrations. Iron oxide precipitation stemming from oxygenation of reduced well water was observed at both wells in the form of staining around the faucets. No iron was detected in groundwater from well COLU_3674. The three wells show a similar shape when plotted on a Stiff diagram with similar absolute concentrations (Fig. 3.4). When plotted on a Piper diagram (Fig. 3.5) the major ion chemistry of all three wells fall in the calcium-sodium and bicarbonate-calcium-sodium facies (Back, 1961).



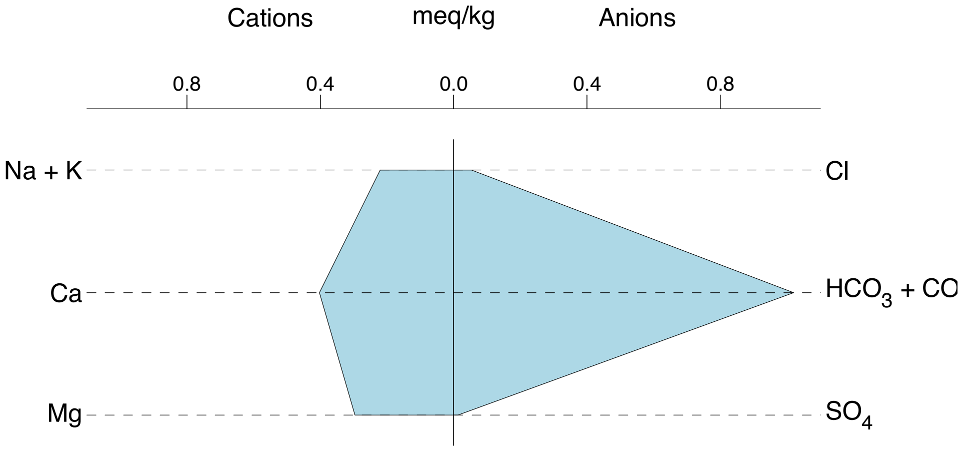


Figure 3.4: Stiff Diagram of wells COLU_3203 E52 (top), and COLU_3674 (bottom) showing the typical groundwater chemistry of groundwater from the flowzone between the Ortley and Wapshilla Ridge members.

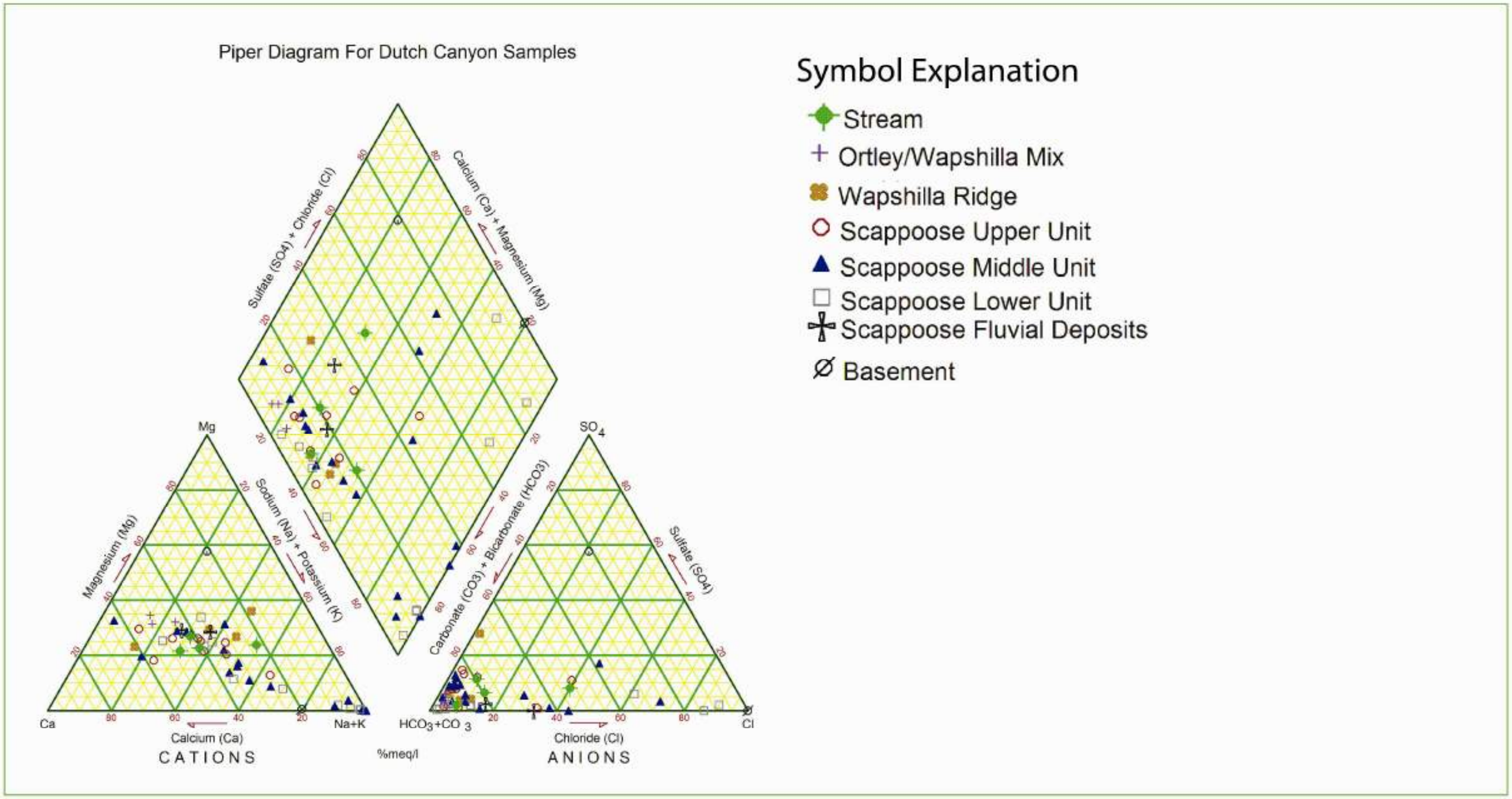


Figure 3.5: Piper Diagram of groundwater and surface water samples collected in 2010 and 2011 from wells in Dutch Canyon.

3.4.1.3 Wapshilla Ridge member, Grande Ronde Basalt

Similar to the Ortley member, the Wapshilla Ridge member is only present at higher-elevations (>190 meters amsl) west of the PHF and near or below sea level east of the PHF. In areas where the Wapshilla Ridge member is present, many wells extend through it and into the underlying Scappoose Formation. Four of the sampled wells were identified as being opened to the Wapshilla Ridge member: wells COLU_322, COLU_53912, COLU_93 and COLU_53503 screened to an intraflow zone; another, COLU_629, was screened across the contact between the Wapshilla Ridge member and the arkosic upper unit of the Scappoose Formation.

The average groundwater temperature in the Wapshilla Ridge member was 12.2 ± 0.9 ºC; the average pH was 6.79 ±0.6. The Eh and specific conductivity of the water within the Wapshilla Ridge member was significantly different depending on location. Eh ranged from 97 - 375 mV with waters from two wells on the east side of the PHF, COLU_53503 and COLU_3186 having values of 97 and 42 mV and D.O. readings less than 1% and waters from wells located on ridges, COLU_322 and COLU_93 having Eh values of 346 and 375 mV and higher D.O. readings. The groundwater in the Wapshilla Ridge member along the ridges is closer to the recharge zone while the groundwater east of the PHF may be located in the regional flow system generally moving towards the Columbia River and the fault may be a barrier to flow, similar to those described near Mosier, Oregon (Burns et al., 2012). The Eh of groundwater drawn from the contact between the Wapshilla Ridge member and the top of the Scappoose Formation was measured at 309 mV.

Specific conductivity showed a similar trend with higher values of 348 and 463 uS/cm measured in samples from the lower elevation (low Eh) wells installed east of the PHF and readings of 87 and 111 uS/cm in the higher elevation and higher Eh wells; water from the well opened across the Scappoose Formation/Wapshilla Ridge member contact had a specific conductivity of 55.8 uS/cm.

The Stiff diagrams in Fig. 3.6 illustrate the differences in major ion chemistry between samples collected from wells located on the ridges and samples located in the lower elevations east of the PHF. Groundwaters in the lower elevation Wapshilla Ridge basalts have higher overall concentrations (>2.0 meq/kg) and higher levels of Ca than Na + K and Mg while groundwater from the higher elevation Wapshilla Ridge wells have lower overall ion concentrations (< 1 meq/kg) and are depleted in Ca compared to Na + K and Mg. This could be due to increased residence times of the lower elevation groundwaters in low producing aquifers or to flushing of high TDS Scappoose Formation groundwater into the lower elevation Wapshilla Ridge member across the Portland Hills Fault where the strong west to east gradient would move groundwater from the Scappoose Formation to basalt units. The Na and Mg in the higher elevations may be sourced from precipitation, as the concentrations are low. The difference in concentrations could be due to ion exchange as, according to well report descriptions, the higher elevation basalts are highly weathered compared to the lower elevation basalts, and the clay in the weathered basalts may be exchanging the Ca in the groundwater for Na and K. Both Na^+ and K^+ are both more likely to be exchanged than Ca^{+2} as the divalent ions are more strongly bonded than the monovalent ions. The Ca^{+2} would be sorbed to the mineral surface preferentially over the monovalent ions. Mineral saturation indices also show a marked difference, with groundwaters from the three wells at lower elevations saturated with respect to siderite ($FeCO_3$). This could be a factor in well screens in the area becoming clogged as the siderite allows higher concentrations of dissolved iron in the water which then leads to precipitation of iron oxides when ferrous iron is oxidized to ferric iron in the well casing. The lower conductivities and total dissolved solids and positive Eh values in samples from the higher elevation wells suggests shorter residence times relative to the waters in the lower elevation wells.

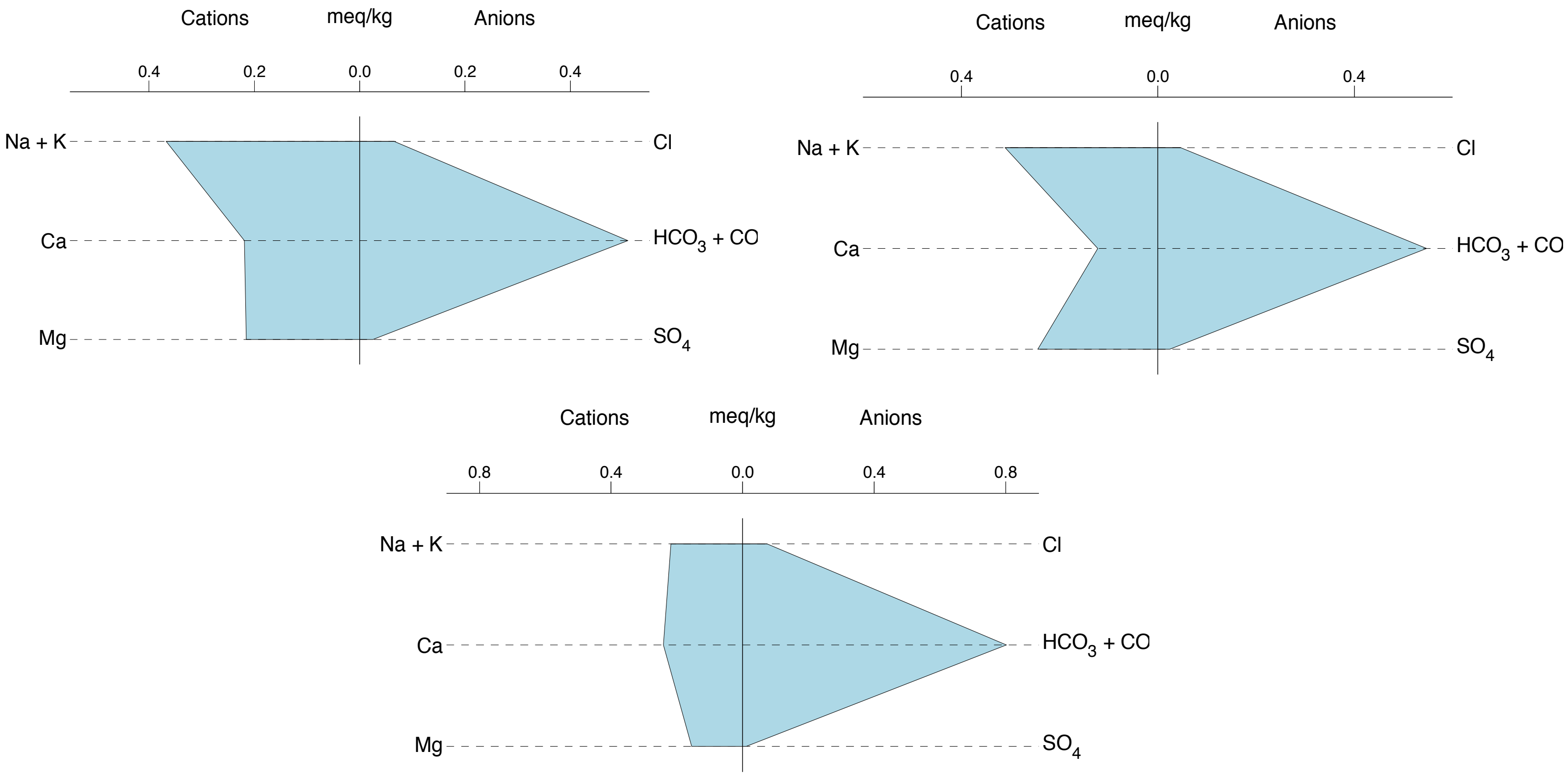


Figure 3.6: Wapshilla Ridge Stiff diagrams showing two major groundwater chemistry trends. (Top L to R) COLU_322, COLU_93, and COLU_53503 (Bottom). The top two diagrams are from the higher elevations and the bottom diagram is from a

3.4.1.4 Upper Scappoose Hydrostratigraphic Unit

The upper hydrostratigraphic unit of the Scappoose Formation is the shallowest hydrogeologic unit below many homes along the lower slopes of Dutch Canyon, above 100 meters elevation west of the Portland Hills Fault. Although the upper Scappoose hydrostratigraphic unit may be the most readily accessible, most wells in these areas are completed in lower and middle Scappoose hydrostratigraphic units. None of the sampled wells east of the PHF were screened to any of the Scappoose hydrostratgraphic units. A total of six wells were sampled that are screened into the upper unit, with one well, COLU_3012, opened to the contact between the overlying Wapshilla Ridge member and upper unit of the Scappoose Formation. In addition to the wells, three springs were sampled that were identified discharging water from the upper unit, with one, sample S-SP, near the contact with the middle unit, which may explain the presence of the spring itself. In each of these instances, the spring water was fed into water storage tanks from which the water samples were obtained. This was necessary due to the low flow rate of the springs and the fact that they were difficult to directly access. The springs in this area of Dutch Canyon do not appear to be related to the landslide complex but rather a likely lithologic change from the arkosic upper unit of the Scappoose Formation to the finer grained middle unit.

Groundwater temperature in the upper unit of the Scappoose ranged from 12.2 - 15.9 ºC (Table 3.3), with an average value of 12.9 ºC and a standard deviation of 1.2 ºC. Specific conductivity, Eh, D.O., and pH showed ranges similar to those seen in the basalt units. Specific conductivity ranged between 82.1 uS/cm - 372 uS/cm with a standard deviation of 90 uS/cm, and total dissolved solids ranged from 37 mg/L - 220 mg/L.

Lower conductivity values in well water were associated with pH values of 6.3 and 6.5, negative Eh and D.O. less than 1%, while higher conductivity values were associated with higher pH values and positive Eh values.

Stiff diagrams (Fig. 3.7) show a relatively consistent pattern for all groundwater samples from the upper unit of the Scappoose, with Ca and HCO_3 being the dominant ions. Analysis of major ion chemistry using Visual MINTEQ shows a similarity between wells with similar measured field parameters. In the wells with low Eh values, waters are near equilibrium with respect to siderite (SI values of -0.6 and -0.7). Plotting on Piper diagram shows the groundwater is mainly calcium-magnesium-bicarbonate facies with one sample, S-SP, showing considerably higher Cl than the others. This sample was collected from a holding tank collecting spring water which could not be thoroughly purged.

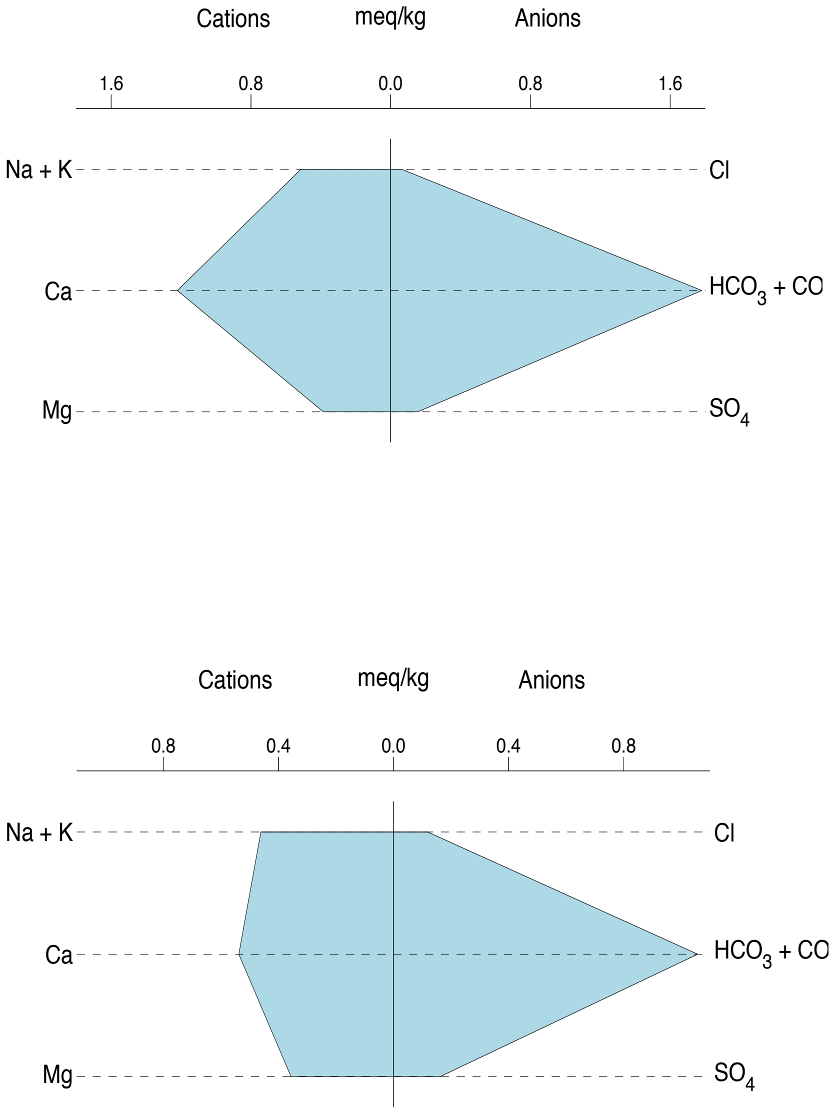


Figure 3.7: Stiff diagrams of Upper Scappoose unit showing characteristic shape of groundwater in the unit. COLU_5153 (Top) and COLU_51176 (Bottom).

3.4.1.5 Middle Scappoose Hydrostratigraphic Unit

Fifteen of the sampled wells – the highest number – were identified as being open to the middle hydrostratigraphic unit of the Scappoose Formation. Most wells installed in this unit were drilled through overlying units. All wells drawing from the middle Scappoose are located west of the PHF.

Groundwater temperatures in the middle unit of the Scappoose Formation ranged between 11.4 ºC - 18.2 ºC with a mean temperature of 13.4 ºC, a median temperature of 13.2 ºC and a standard deviation of 1.7 ºC. The 18.2 ºC value was from COLU_52774 which was sampled from a water storage tank and may not be representative of the true water temperature of the unit. Specific conductivity values were measured between 108 uS/cm - 1,163 uS/cm with a mean of 208 uS/cm, a median value of 320 uS/cm, and a standard deviation of 242 uS/cm. The Eh of the water ranged between -48 mV - 547 mV with a mean of 253 uS/cm, a median value of 92 mV, and a standard deviation of 168 mV.

All four well samples with Eh values <100 mV were near saturation with respect to siderite (SI values of -0.08 - +0.36). Several (e.g., COLU_3158 and COLU_50634) appeared near saturation with respect to hydroxyapatite and or vivianite (SI values of -0.25 to 0.39). This, together with the higher TDS values and the dominance of Na-bicarbonate waters suggests that much if not most of the groundwater moving in the middle unit is part of a more regional and more sluggish flow system that may be poorly flushed and or that has some degree of mixing with deeper, possibly connate waters

Stiff diagrams for middle Scappoose groundwaters show a dominant and uniform Na+K-bicarbonate pattern (Fig. 3.8), regardless of total dissolved solids levels or specific conductivities values. This is contrasted with the lack of cation dominance to slight Ca dominance in the overlying units.

With the exception of well COLU_50634, which was chemically unique to all other middle Scappoose wells, no wells were in equilibrium or near saturation with respect to any iron phase mineral, although most were oversaturated with respect to quartz and chalcedony. Well COLU_50634 is installed to an elevation of 18 meters amsl, near the contact of the middle and lower units of the Scappoose Formation. It is here assigned to the middle unit due to the well report description listing blue sandstone throughout.

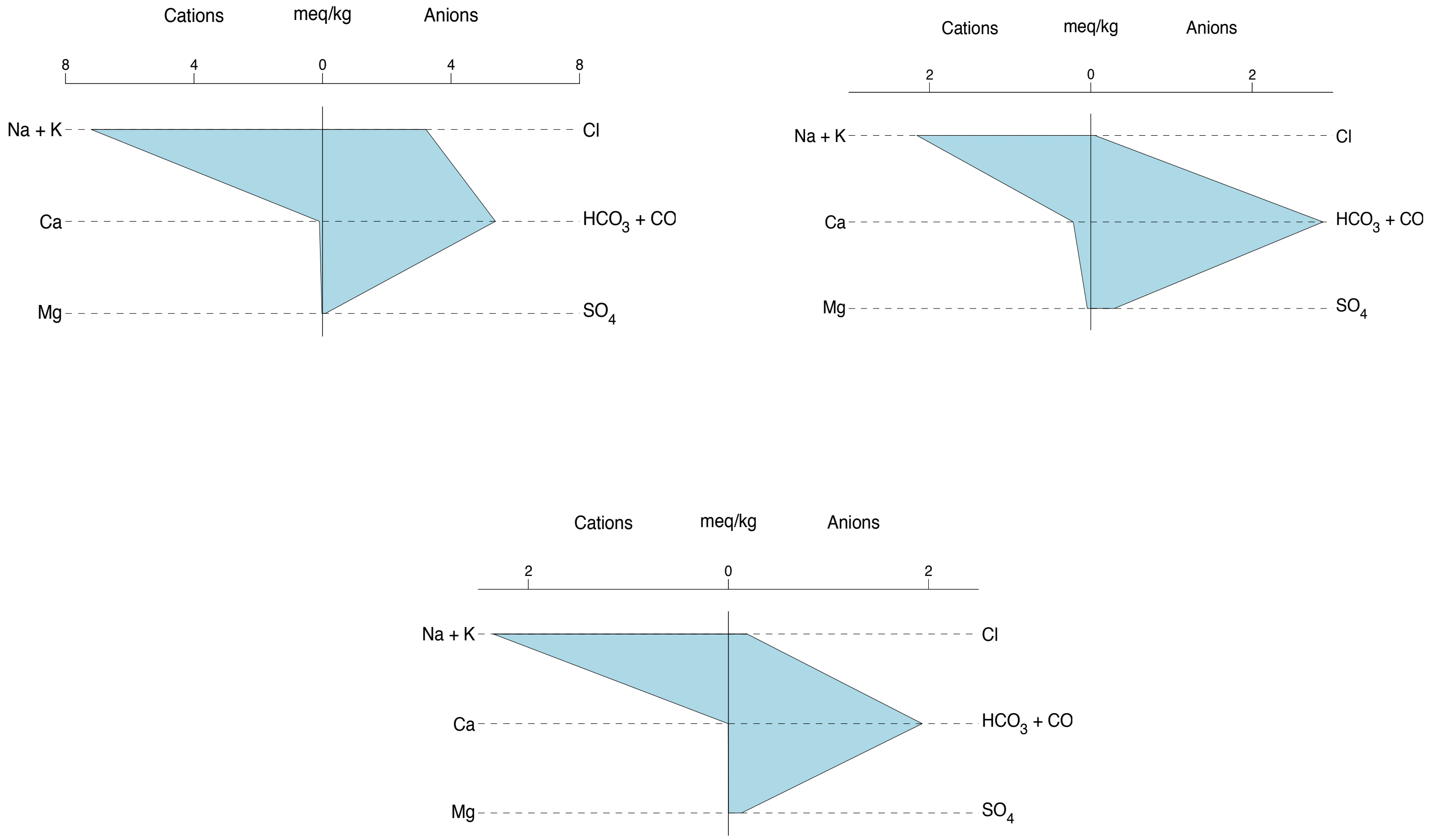


Figure 3.8: Typical Stiff Diagram for wells in the Middle Scappoose Unit. Na + K concentrations are characteristically high compared to other cations.

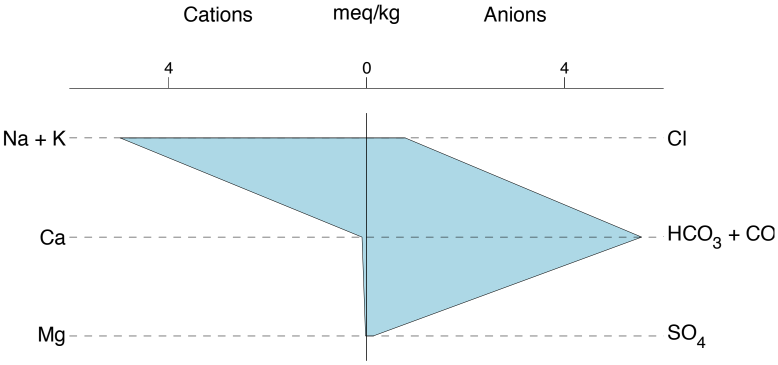
3.4.1.6 Lower Scappoose Hydrostratigraphic Unit

Twelve of the sampled wells were constructed in the lower Scappoose hydrostratigraphic unit. No outcrops of the lower unit were observed in the field area, so all wells tapping into the unit are drilled through overlying units, including shallow alluvial fill near the South Fork Scappoose Creek. As with the other Scappoose Formation units, all wells open to this unit are located west of the PHF.

Groundwater temperatures in the lower unit ranged between 12.4 ºC - 14.6 ºC with a mean temperature of 13.5 ºC and a standard deviation of 1.7ºC. Other field parameter measurements of groundwaters from the lower unit were highly variable. The specific conductivity of the water varied from 150 uS/cm - 1814 uS/cm with a mean value of 611 uS/cm, and a standard deviation of 489 uS/cm. Measured pH values in the unit were between 6.36 - 9.3 with a mean value of 7.7 and a standard deviation of 0.9. The high pH value of 9.3 is in a 347 m deep well on the northern rim of Dutch Canyon, much deeper than the other wells drawing from the lower unit. The Eh of the lower unit of the Scappoose Formation was mostly negative with a range from -44 mV - +326 mV and an average value of 182 mV and standard deviation of 119 mV. The lower unit of the Scappoose Formation unit had the lowest dissolved oxygen levels in the field area with seven of the ten wells below 1 mg/L O_2.

Major ion analysis revealed a similarity among some wells in the lower unit of the Scappoose to the middle unit of the Scappoose, and some to wells in the upper unit of the Scappoose. Over half the well samples from the lower Scappoose unit were Na + K-bicarbonate waters. Several wells had higher concentrations of Ca than Na + K. These wells are also open throughout so they may be drawing from a mix of water from the units. Due to the presence of clay in the units, as noted in many well reports, ion exchange could also be responsible for the variance in concentrations as Ca will often be exchanged with Na on clay minerals, increasing the Na concentration in groundwater. Groundwater from three wells appeared to be in equilibrium with calcite (SI values between -0.1 and 0.5).

Two wells, COLU_50330 and COLU_3040 located 200 meters apart spatially and both constructed to the same unit (COLU_3040 is 50 meters deeper) had very different chemistries as illustrated by the stiff plots in Figure 3.9. In COLU_3040, groundwater appeared to be in equilibrium with calcite, siderite, dolomite, and quartz (SI values between -0.2 and 0.5 while in COLU_50330, christobalite, which is not stable at surface conditions, and two amorphous quartz minerals are in equilibrium. In personal communication with the property owners of both wells, it was learned that multiple previous attempts to locate groundwater were performed, with at least three other wells, each 300 or more meters deep, completed at each site but yielding no or insufficient flows. With so many dry wells on both properties, lateral and vertical connectivity in this part of the unit appears to be minimal to nonexistent and groundwaters are chemically unique, despite being geographically close. These two wells may be open to different water-bearing zones within the lower unit as they are 50 meters apart vertically. The depositional environment of the unit in this part of the Scappoose Formation has been described as alternating between marine and nonmarine sand and siltstone. Lenses of varying lithologies and permeabilities would be expected in this environment and could produce heterogeneous flow systems with varying levels of hydraulic connectivity.



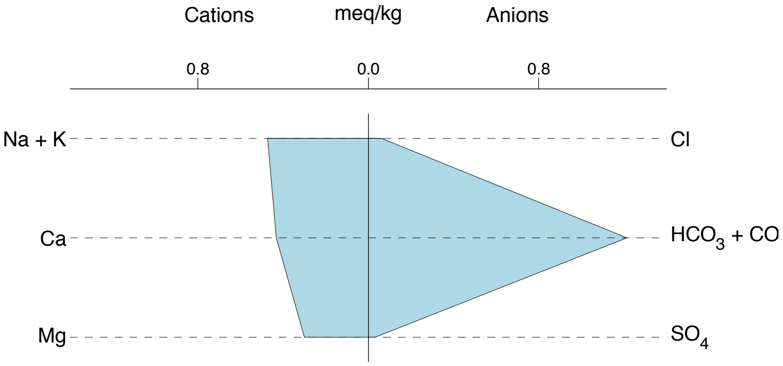


Figure 3.9: Wells COLU_3040 (top) and COLU_50330 (bottom) in the Lower Scappoose displaying the two prominent Stiff diagram shapes in the unit.

3.4.2 Comparison of Water Chemistry Between Units

Some chemical variations between the groundwater in different hydrostratigraphic units in Dutch Canyon are evident, as are some spatial differences in water chemistry within the same unit, which will be discussed in the following section.

The most distinct differences in water chemistries were between the lower (or lower and middle) Scappoose hydrostratigraphic units and the overlying units (Table 3.7). Specifically, as evidenced in Table 3.9, the waters in the lower and middle Scappoose units had significantly greater salinity (as measured independently by TDS and specific conductivity) than did those from the upper Scappoose Formation (median TDS values of 245 vs 127 mg/L; $p = 0.007$) or from the upper Scappoose combined with the Ortley and Wapshilla Ridge member samples (median TDS values of 245 vs 136 mg/L; $p = 0.007$). Groundwater in middle and lower units of the Scappoose Formation mostly plot as sodium bicarbonate to sodium bicarbonate-chloride type while the groundwaters in the upper unit and the basalt units are predominantly calcium-bicarbonate. The prevalence of Na and K in the lower and middle units of the Scappoose Formation in comparison to the upper unit and the Grande Ronde Basalts may be due to ion exchange in the clay rich lower units which have a higher amount of alkali metals to exchange Na and K with Ca, depleting the groundwater concentration of Ca. There is also a significant difference in pH values in the lower and middle Scappoose vs. the upper Scappoose groundwaters (median values of 7.42 vs 6.77; $p = 0.030$). Groundwater in the upper unit of the Scappoose Formation was also typically higher in dissolved oxygen compared to the middle and lower units.

The waters within the lower and middle units of the Scappoose Formation are chemically similar but diverge in some areas. The groundwater in the lower unit of the Scappoose is more reducing with lower dissolved oxygen levels than the groundwater in the middle unit. The lower unit also has a higher mean specific conductivity compared to the middle unit. These conditions are likely due to the lower unit being confined by clay and silt in the middle unit resulting in slightly less recharge of fresh, oxygenated water.

There were fewer samples collected from the Ortley and Wapshilla Ridge members but some differences in water quality were observed between samples collected from higher and lower elevations, across the Portland Hills Fault. Groundwaters in both members tend to have lower pH, higher TDS, and lower Eh in the lower elevation wells than the higher elevation wells. This is likely due to the lower elevation wells being part of the deeper regional flow system that has passed through the Scappoose Formation to the west of the fault while the higher elevation wells are closer to recharge areas and contain water with less residence time.

Table 3.7: Descriptive statistics for water chemistry parameters from 2010-2011 sampling round of wells & springs (n = 48; excludes A3-SW (gas well)) Note: Br, NO3, & HPO4 are not included because they were not detectable in majority of samples.

Parameter (mg/L unless otherwise stated)	Missing	Mean	Std Dev	Std. Error	C.I. of Mean	Range	Max	Min	Median	25%	75%
Na	0	40.7	74	10.6	32	467	471	3.5	12.8	9	43
K	0	3	1.6	0.2	0.2	8.9	9.3	0.4	3	1.8	3.7
Ca	1	15.7	12	1.7	4.6	43.8	43.8	0.1	11.9	6.4	22.4
Mg	1	5.1	3.5	0.5	1.3	12.9	13	0.2	4.3	2.7	8.4
Fe(tot)	7	3.4	3.6	0.9	1.9	11.2	11.2	0	2.6	0.1	6
Cl	0	34	106	15.3	48.8	699	700	1.2	2.7	2	14.9
HCO3	0	111	69	10	19.1	334	346	12	104.9	63	142
SO4	1	6.6	8	1.2	3.6	49.8	49.9	0.1	4.5	1.2	9.2
F	3	0.2	0.1	0	0	0.3	0.3	0.1	0.2	0.1	0.3
As(tot)	7	0.002	0.0037	0.0008	0.0017	0	0	0	0	0	0
pH	0	7	0.7	0.1	0.3	2.9	8.5	5.6	7	6.5	7.4
Temp(C)	0	12.8	1.6	0.3	0.6	9.5	18.2	8.7	12.5	12.3	13.2
SpCond(uS/cm)	0	359	347	62	127	1741	1814	73	314	151	384
D.O.(%_sat)	0	36.6	37.4	6.7	13.7	101	101	--	19	1.3	74
Eh(mv)	0	59.2	168	30.3	61.8	709	547	-162	80	-91.8	126
Hardness_Carb	0	59.9	44.2	7.9	16.2	151	151	0	48.1	23.8	88
TDS(mg/L)	0	223	245	43.9	8	1381	1396	16	182	100	251

Table 3.8: Descriptive statistics for field measurements of water chemistry parameters from 2010-2011 sampling round of wells & springs

Hydrogeologic Flow Unit	Ortley (n=3)	Wapshilla Ridge (n=4)	Scappoose Upper Zone (n=9)	Scappoose Middle Zone (n=15)	Scappoose Lower Zone (n=12)
Mean pH	7.33	6.65	6.77	7.25	7.71
Std Dev pH	0.2	0.4	0.6	0.7	1.0
Max pH	7.52	7.09	7.76	8.7	9.3
Min pH	7.11	6.19	6.09	6.36	6.02
Mean Eh (mV)	-32	40	118	53	-18
St Dev Eh (mV)	190	141	106	173	196
Max Eh (mV)	187	175	323	547	431
Min Eh (mV)	-158	-103	-31	-248	-244
SpC Mean (uS/cm)	283	207	182	371	611
St Dev SpC (uS/cm)	87	174	101	249	516
Max SpC (uS/cm)	348	463	372.3	1115	1814
Min SpC (uS/cm)	184	87	55.8	95	150
Mean T (oC)	13.53	11.40	13.17	13.41	13.47
St Dev T (oC)	0.6	1.2	1.3	1.3	1.9
Max T (oC)	14.2	12.5	15.9	16.3	18.2
Min T (oC)	13.2	10	11.6	11.4	11.5
Mean O2 (mg/L)	3.35	4.46	5.06	2.69	1.91
St Dev O2 (mg/L)	5.7	5.1	4.0	3.1	2.9
Max O2 (mg/L)	9.9	9.62	10.63	9.08	9.25
Min O2 (mg/L)	0.05	0.06	0.09	0.04	0.04

3.4.3 Chemical Difference Due to Geographic Location

While there are chemical differences between the hydrogeologic flow units, geographic location was also a reliable indicator of water chemistry within the CRBG units and the Scappoose Formation. Generally, wells constructed at locations closer to the valley floor yielded water that was higher in conductivity, lower in dissolved oxygen and Eh, and were often higher in iron concentrations than wells that were located at higher elevations along the canyon slopes. Many of the higher elevation wells are screened to the Wapshilla Ridge and Ortley members of the CRBG. These units are near the recharge area and the groundwater has fewer dissolved solids in it and has had less residence time than in lower elevations. The basalt units are offset by the Portland Hills Fault along the eastern margin of Dutch Canyon, where they are the bedrock near sea level. The groundwater in the lower elevation basalt units is typically higher in conductivity and lower in dissolved oxygen and Eh. This is most likely due to the west-east regional flow in groundwater resulting in water with greater residence times that likely passed through the Scappoose Formation prior to entering the downthrown basalt units. The chemical difference between groundwater in the Scappoose Formation is partially a function of which unit the well is open into, as the upper unit of the Scappoose Formation is distinctly different from the middle and lower units throughout the study area. However, wells constructed to the middle and lower units away from the valley floor were still more likely to yield water with higher Eh and higher D.O. values than wells close to the valley floor in the same unit. Sites COLU_53868, COLU_52774, COLU_3030, and B10-W are all open to the middle unit of the Scappoose Formation and contain water with higher Eh and D.O. values.

The higher elevation wells are closer to the assumed recharge areas for the aquifers and have less residence time than groundwater near the valley floor. The wells lower in the valley are more likely to contain some of the diluted remains of connate waters as evidenced by an increasing trend of Cl concentrations in the middle of the valley. Of the wells sampled, the 12 highest concentrations of Cl were in wells screened to the lower and middle units, in the lower elevations of Dutch Canyon. A regression analysis of Cl controlling for well screen elevation and location yielded a p value of 0.02. The wells in the lower units are also transmitting regional discharge from the larger area around Dutch Canyon, which will have had more water-rock interaction than in the recharge zone. Such deeper flow systems are evidenced by the anomalously high specific conductivity measured for well COLU_3040. This well is over 300 meters deep and not as flushed out as some surrounding wells. In addition, nearly a dozen wells were drilled between this property and the neighboring one, site of COLU_50330, with only two producing usable amounts of water (personal communication Meshell, 2011 and Horn, 2010), suggesting that Well COLU_3040 is tapping an isolated lens of permeable material. This is also supported by the stable isotope results from COLU_3040, which was significantly different from all other wells in the region, suggesting a different flow system of groundwater.

3.4.4 Gas Well Impact

An abandoned natural gas exploration well that was installed in the 1920s has been constantly pumping groundwater under artesian pressures since its completion. A USGS chemical test of the well was done in 1955 that showed an extremely high level of dissolved solids and a specific conductance of 42,400 uS/cm. Field testing of this well as part of the current study indicated a very similar electrical conductivity of 43,600 uS/cm, indicating the discharge is likely to be connate water. For comparison, seawater has an electrical conductivity of around 54,000 uS/cm (McCleskey et al., 2011). As elevated TDS is a problem in local groundwaters, particularly from wells located in the lower elevations of Dutch Canyon, there is a concern about the potential impact of this well on the local groundwater.

The gas exploration well yields water due to artesian pressure at less than 0.004 m^3 (1 gallon) per minute, as measured in the field. The discharged water flows from the well downhill onto a concrete area for ~10 meters and another ~10 meters over soil where it discharges into the South Fork Scappoose Creek. The creek is between 5 and 6 meters wide in this area and between 1 and 2 meters deep. With less than 0.004 m^3 entering the stream each minute, it can be assumed stream water chemistry is not significantly affected by the saline water from the well. This is observed in the similarity between water collected at sample point SFSCAPPOOSECREEK directly downstream from the well to water collected directly upstream at sample point J-ST-0823.

A greater potential source of contamination from the gas well is through subsurface leakage. Due to the age of the well, subsurface leakage is a possibility somewhere along its significant length. As the Scappoose Formation was formed in a mainly marine setting and aquifer transmissivity values are mostly low, saline waters are likely at depth. As the gas well has been discharging water since the 1920s, a dispersion pattern of saline waters through upper groundwater flow zones would be expected if the gas well were leaking. It would be possible for some groundwater mounding to occur around the well, if it were leaky. Water well level measurements were not made as part of this study and there are few reliable records surrounding the well. As such, mounding cannot be ruled out, but there is no evidence to support it. There is no clear evidence that the gas well, COLU_3167, is having any significant impact on the quality of shallow groundwaters. If it were leaking, the highest TDS (or Cl-) concentrations might be expected in the closest well, which is COLU_51056, located on the same property. However, the highest specific conductivity levels are found over 1 km down gradient in well COLU_3163. Both wells draw groundwater from similar elevations, with COLU_51056 constructed to a bottom elevation of 57 meters (with about 3-5 m of uncertainty due to the considerable relief on the property) and COLU_3163 open at 42-48 meters elevation. Because of the heterogeneities of the middle unit of the Scappoose Formation it is possible that these two wells are hydraulically isolated, which could mean that preferential flow from the gas well could bypasses COLU_51056. However, a k-means cluster analysis of groundwater chemistries resulted in the gas well waters segregated in a cluster by itself with wells COLU_51056 and COLU_3163 in a separate cluster by themselves, and the rest of the wells on other clusters, suggesting these two wells are connected to each other.

In order to predict the degree of groundwater mixing that must occur for the elevated specific conductivity levels to be possibly attributed to the leaky gas well, a mixing model in PHREEQC was completed. In this model, the groundwater chemistry of the sample collected from the gas well was mixed with the sample containing the highest salinity in the middle and lower units of the Scappoose Formation that was unlikely to be an end member for the wells potentially affected. The well selected for this was COLU_3163, located 1 km east of the gas well, screened to the lower unit of the Scappoose Formation, with a sampled groundwater specific conductivity of 1814 uS/cm.

The result of the groundwater mixing model was that 5% of the groundwater within the middle and lower units of the Scappoose Formation must be derived from the gas well in order to produce the levels measured in the water of COLU_3163. As the source is a single well slowly leaking, it would be highly unlikely that 5% of the groundwater volume in up to 200 meters of saturated thickness can be attributed to it. From the mixing model alone it is unlikely the gas well is responsible for the elevated conductivity levels in the Scappoose Formation but this can be further tested by comparing the stable isotope readings for the area. If significant groundwater mixing between the well and the aquifer is occurring, the stable isotope values should be influenced by the leaky gas well, for which measured isotopic values were significantly different than groundwater in the rest of Dutch Canyon. A similar mixing ratio of 5% water from the gas well would pull the isotopic values of groundwater towards a less negative value for both deuterium and Oxygen-18. This change would be reflected by a cluster of points higher and to the right of the other samples and relative to the SMOW line in Fig. 3.1. No separate cluster is visible as many of the samples from the Lower and middle unit of the Scappoose Formation are clustered near one another, including samples near the gas well with elevated specific conductivity values.

It should be noted that wells (including COLU_51056) that experience problems with salty water are almost exclusively in the discharge zone of the valley floor, where deeper, regional groundwaters with higher conductivities would be expected to surface.

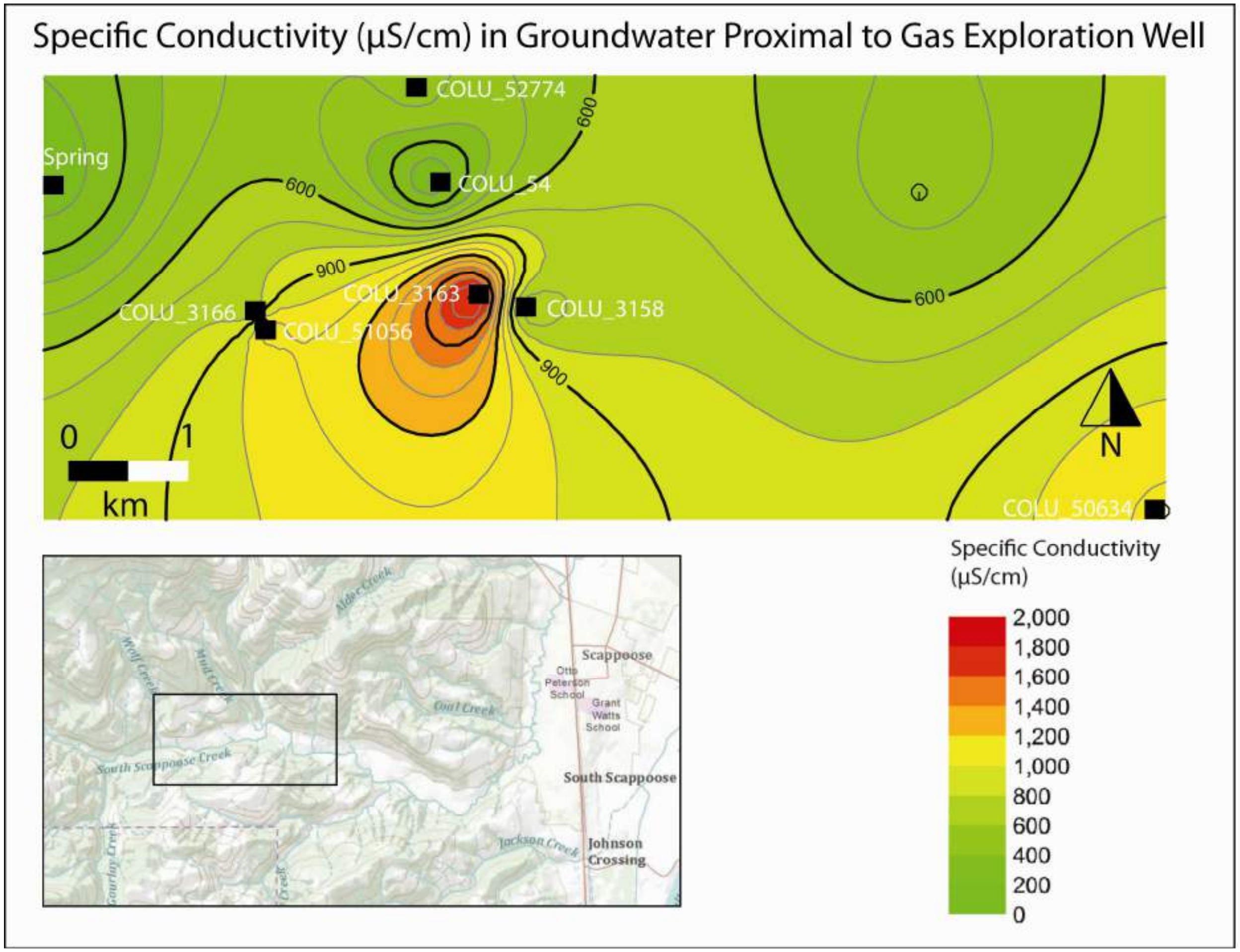


Figure 3.10: Groundwater values for specific conductivity near the gas exploration well on the property of COLU_51056. Data show conductivity does appear to be sourced from the leaky gas well.

CHAPTER 4. CONCLUSIONS

In this study, I identified five significant hydrostratigraphic units underlying the Dutch Canyon study area and determined their associated hydraulic properties and water qualities. The five units are the Wapshilla Ridge and Ortley members of the Grande Ronde Basalt of the Columbia River Basalt Group and the upper, middle, and lower hydrostratigraphic units of the Scappoose Formation.

The Portland Hills Fault offsets units along the eastern margin of Dutch Canyon. The Scappoose Formation is only accessed by wells located west of the fault, but the Grande Ronde Basalt units are accessed by wells on both sides of the fault. The majority of Dutch Canyon is west of the fault where the basalt units are present above 200 meters along the upper portions of the valley flanks and the ridge tops. As a result, the majority of domestic wells draw groundwater from one of the three hydrostratigraphic units within the Scappoose Formation.

The basalt units are generally low producing but have relatively better water quality than the Scappoose units. On the east side of the fault, wells installed in the basalts, mainly the Ortley member, often produce higher volumes of water than those west of the fault. However, most homes on the east side of the fault are in areas where residents are now on, or can connect to, city water.

The upper unit of the Scappoose Formation, a non-marine arkosic sandstone, is present throughout the area above 100 meters elevation, generally between 100-200 meters elevation. It is generally accessed by wells constructed on properties along the valley flanks and in deep wells along the ridges.

Below this lies the middle unit of the Scappoose Formation, which is present throughout Dutch Canyon and varies in thickness between a few meters to 80 meters. This unit is a poorly sorted mixture of sand and silts that was deposited in marine and near marine environments. Many wells in the middle unit are very low producing, with some property owners forced to purchase a holding tank to store water in order to have enough to meet basic demands. Some wells drilled into the unit have not produced any useable quantity of water.

Below the middle unit is the lower unit of the Scappoose Formation. This unit is described as grey marine sandstone with common occurrences of silt. Its upper boundary is at ~20-40 meters elevation and the lower boundary of this unit is not present in any well logs in Dutch Canyon; its thickness is assumed to be around 100 meters. This unit is also characterized by low well yields.

The primary groundwater quality issue in Dutch Canyon is high TDS or “salty” water, particularly for wells completed in the lower or middle units of the Scappoose Formation. Nearly 20% of the wells sampled that were completed in these units (5 of 27) yielded groundwater that exceeded the U.S. Environmental Protection Agency’s National Secondary (non-enforceable) Drinking Water Regulation standard of 500 mg L^{-1} TDS. These units are distinctly more fine-grained than the overlying unit. The dissolved solids likely result from long groundwater residence times in the marine sediment and possibly some contribution from connate waters, as suggested by higher Cl concentrations relative to other units.

The upper unit of the Scappoose Formation and the overlying Grande Ronde Basalt members generally yield water with lower TDS contents (mean < 200 mg L^{-1}; maximum = 342 mg L^{-1}; n = 20). However, much of the population of Dutch Canyon resides in areas – generally below 150 meters elevation - where middle and lower units are the only available aquifers.

Some concern exists over the impact of a natural gas exploration well that may be leaking highly saline water into the Scappoose Formation. However, mixing models utilizing TDS or isotopes, as well as the spatial distribution of groundwater with high TDS contents indicate that any impact of the gas well on shallow aquifer water quality is minimal and it is concluded that the gas well is not responsible for the general salty groundwater in Dutch Canyon.

Dissolved iron and sulfur are aesthetic issues with the groundwater that may not be avoided if a well draws from one of the lower units. Many wells sampled within the lower and middle units of the Scappoose produce low Eh waters and iron precipitation due to oxidation of the water may lead to clogged well screens and stained fixtures.

Dissolved arsenic does not appear to be an issue for domestic wells in Dutch Canyon. Water from one of the sampled wells contained arsenic at a concentration that exceeded the U.S. Environmental Protection Agency's National Drinking Water Regulation standard of 0.010 mg L^{-1} As. However, the well is only used for irrigation in an area that is served by the City of Scappoose's water system and is completed in a shallow alluvial aquifer that is limited in thickness and areal extent and which is not targeted for domestic drinking water.

It can be assumed that groundwater availability and water quality will be a concern for new development in the area. Low recharge rates and low permeability suggest that increasing rates of groundwater extractions from area aquifers could have the potential to lower groundwater levels and affect stream flows during dry summer months. Future studies in the area could focus on a detailed model of the aquifers for predictive estimations of groundwater availability.

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Appendix 1. Dutch Canyon Well Database Spreadsheet

A spreadsheet titled “Dutch_Canyon_Well_Database.csv” is available as a supplemental file to this thesis. It lists all wells in Dutch Canyon with details for location, elevation, well depth, hydrostratigraphic unit, aquifer properties (if available), field parameters (if sampled), and water chemistry (if sampled). It is 152 KB and requires Microsoft Excel to view.