Hydrogeological Investigation of Stacked Quaternary and Late Cretaceous Bedrock Aquifers, Vancouver Island, British Columbia, Canada

Gypsy C. Fisher
BC Ministry of Environment, Victoria, British Columbia, Canada
Vic M. Levson
BC Ministry of Energy, Mines and Petroleum Resources, Victoria, British Columbia, Canada
Diana M. Allen
Simon Fraser University, Burnaby, British Columbia, Canada

ABSTRACT
Two adjacent groundwater observation wells were drilled within the Comox Coalfield on Vancouver Island, BC; one in bedrock (146.9 m) and one in surficial sediments (7.3 m). A water-bearing fracture zone 3 m wide was encountered at 135 metres depth coincident with two Comox coal seams. Dissolved methane gas was detected in the bedrock aquifer and Schoeller diagrams reveal that the gas in bedrock is coal related. A pumping test in the deep well suggests that there is unlikely any hydraulic communication between the bedrock and surficial aquifers, but due to difficulties with the pumping test, this conclusion is uncertain.

RÉSUMÉ
Deux puits d'observation ont été forés dans le bassin charboneux de Comox sur l'île de Vancouver, en Colombie-Britannique; un dans la roche (146.9 m) et un en sédiments surficiels (7.3 m). Une zone fracturée 3 m de large a été rencontrer à 135 mètres de profondeur, coïncidente avec the charbon du Comox. Le méthane dissous a été détecté dans l'aquifère rocheuse et les diagrammes de Schoeller indiquent que le gaz est charbon connexe. Un essai de pompage dans le puits profond suggère qu'il y ait peu probable n'importe quelle communication hydraulique entre l'aquifère rocheuse et l'aquifère surficielle. Mais dues aux difficultés avec l'essai de pompage, cette conclusion est incertaine.

1 INTRODUCTION

The hydrogeology of the Oyster River area of the Comox Coalfield on Vancouver Island, British Columbia (BC) was investigated. As part of this subsurface study, the potential for hydraulic connection between the fractured sedimentary bedrock of the Late Cretaceous Nanaimo Group and the overlying unconsolidated Quaternary aquifers was assessed. With the onset of new oil and gas industries such as coalbed gas (CBG) development as well as increasing interest in groundwater resources within the region, the potential of user conflict arises. Consequently, investigating the region's hydrogeology and potential for aquifer communication will aid in management decisions regarding this communal natural resource.

1.1 The Comox Coalfield on Vancouver Island, BC

The Comox Coalfield, one of two major coalfields on Vancouver Island, has a total coal resource in the range of 3 billion tonnes and an *in situ* gas resource of about 0.65 trillion cubic feet (tcf) (Bickford and Kenyon, 1988; Ryan *et al*., 2005). The major coal seams of interest are located within the lower strata of the Late Cretaceous Nanaimo Group sedimentary sequence (Mustard, 1994). Overlying the basement Karmutsen volcanics, the Dunsmuir and Cumberland members of the Comox Formation are host to the region's significant coal resources. The coalbed gas reserves of the Comox Coalfield lie below 450 m and may extend to depths as great as 1,500 m, well within the depth range of coalbed gas extraction techniques (Cathyl-Bickford, 1991). Gas compositions obtained from coal exploration programs within the coalfield reveal that the gas is of acceptable quality for a gas-transmission system.

There have been 89 test holes for CBG drilled in BC since 1984; 58 of them from 2001 to present, 14 were drilled in 1984 on Vancouver Island, and one well drilled in 2001/02 but which is now inactive (Ryan, 2002; Ryan *et al*., 2005). Few holes have been drilled for coalbed gas pilot projects within the Comox Coalfield, so there are limited data to determine the possible impacts of future CBG activities on the regional hydrogeology. In an attempt to address this question with the limited data available, the Oyster River study focuses on the hydraulic connectivity and aqueous geochemistry of the stacked surficial and fractured bedrock aquifers, the bedrock host to several coal seams.

2 STUDY AREA

The study are is situated on the central-east coast of Vancouver Island, British Columbia (Figure 1). The Oyster River originates in the mountains of the Forbidden

Plateau and drains an approximate area of 376 km^2 at its mouth before discharging to the Strait of Georgia (Nagpal, 1990).

As part of a regional study to assess the hydrogeology of the Comox Coalfield, two adjacent (paired) groundwater observation wells were completed in the study area. The well sites are located west of the Black Creek gravel pit, approximately 10 km inland from the Strait of Georgia. This area is within Vancouver Island's eastern coastal lowlands, between the Beaufort Mountain Range to the west and the Strait of Georgia to the east.

The hydrostratigraphy of the Black Creek gravel pit area has been identified as a laterally variable, unconfined, surficial aquifer (Fisher, 2009). The uppermost pebble to cobble gravel is thought to act as a highly permeable source aquifer, transmitting water down to the underlying sand and gravel. Both units are considered capable of storing and transmitting groundwater, acting together as a regional, unconfined, surficial aquifer. The considerable variability in the texture of the underlying unit indicates that the groundwater flow pattern would be influenced by the conductive sand and gravel beds, and diamicton lenses having little to no permeability that would act as barriers to flow. Given the considerable geographic extent of the surficial deposit exposed at the Black Creek gravel pit, it is believed to potentially be a significant groundwater resource for the local area.

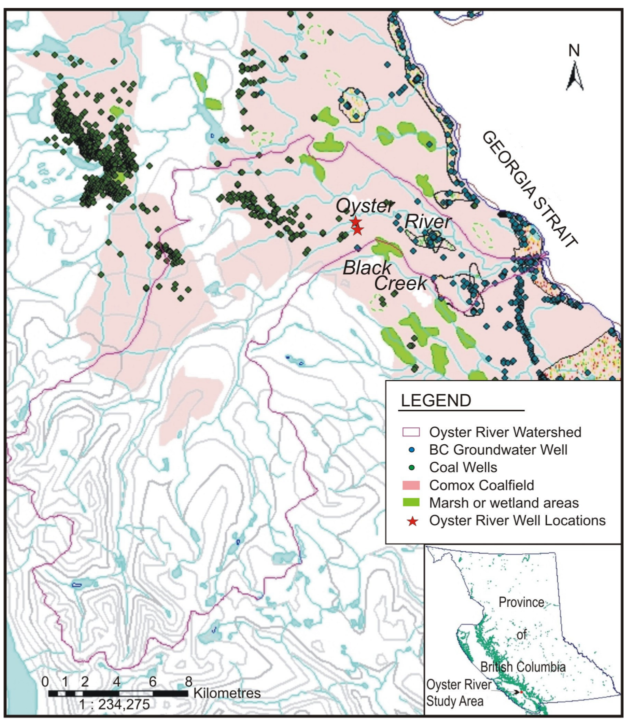

Figure 1. Oyster River Location Map.

3 PREVIOUS WORK

East of the study area are several surficial and bedrock aquifers comprised of Capilano Sediments and the Nanaimo Group sedimentary bedrock sequence with local water-bearing fractures encountered within the upper 60 m (BC MoE, 2001). The bedrock and surficial geology of the region has been primarily mapped by Fyles (1963), Jungen (1975), Bickford and Kenyon (1988), and Bickford *et al.* (1989, 1990). The surficial deposits in which the Black Creek gravel pit and Oyster River wells are located has been mapped as a large elongate landform described as a gravelly, level fluvial terrace that is gently undulating and moderately rolling (Jungen, 1975).

Little research has been completed with respect to the hydrogeology of surficial sediments in the region. Hydrogeological studies on fractured aquifers within the Nanaimo Group sedimentary rock have been conducted in the region (Abbey and Allen, 2000; Allen *et al.*, 2001; Allen *et al.*, 2003; Surrette and Allen, 2008). Water quality assessments and monitoring programs have been conducted for major surface water streams throughout the Oyster River watershed and the Comox Coalfield (Nagpal, 1990; BC MEMPR, 2005), as well as for fractured bedrock aquifers on many of the Gulf Islands (Earle and Krogh, 2004; Allen and Suchy, 2001).

4 BOREHOLE SUBSURFACE METHODS

4.1 Drilling, Sampling and Geophysical Logging

Two wells, drilled 10 m apart between March 17th and March 23rd, 2005, were completed to different depths at Oyster River. BC MoE Observation Well #368 (Well Tag Number (WTN) 83156) was drilled to a total depth of 146.9 m and BC MoE Observation Well #369 (WTN 83157) was drilled to a depth of 7.3 m. These wells are henceforth referred to as WTN 83156 and WTN 83157 or as the deep and shallow wells, respectively. Both wells are currently part of the provincial groundwater observation network monitored by the BC Ministry of Environment (MoE). The deep well is open hole throughout the bedrock, without a screen in place. The shallow well is completed with steel casing down to the 1.4 m stainless steel screen placed at the well's bottom.

Borehole geophysical logging was conducted in both wells at the Oyster River site. The Comprobe 1¼" slim line, 4-function multipurpose probe was employed to measure natural gamma ray, density, relative formation electrical resistance, and borehole diameter using a single-arm motorized caliper. The probe's configuration from bottom to top included a 0.06 m x 0.01 m (2½" by ½") sodium iodide crystal for natural gamma ray detection, an AM 241 americium density source with a sodium iodide single density detector 5 cm above, and a single formation resistance electrode joined with a single-prong motorized caliper at the top end.

The data for the paired wells at Oyster River were recorded as the instrument traveled up from the bottom of the wells; the first readings were taken at 146.8 m and 7.0 m below ground surface (bgs) in the respective bedrock and surficial wells. Logging terminated 1.5 m bgs for both wells. The logging rate of the instrument as it moved up each borehole was 1.6 and 0.12 metres per minute for the deep and shallow wells, respectively. Details of the drilling and geophysical logging methods are provided by Fisher (2009).

4.2 Groundwater Pumping & Recovery Test

Pumping and recovery tests were conducted in each well. Of particular interest, and discussed herein, are the results for the deep bedrock well. Details concerning both tests are provided in Fisher (2009).

The pumping test for the deep well (WTN 83156) was conducted for eighty minutes with an extended recovery period of just less than 14 days immediately following. Based on drill cuttings and depths of water-bearing fractures encountered during drilling, a fracture zone was identified at 135 m bgs (-5 m +MSL); the zone is approximately 3 m thick and includes two thin coal seams. The pump intake was situated at this approximate depth. Data were recorded every minute using a Solinst Levelogger Gold 3001 placed approximately 100 m bgs (30.5 m +MSL). Monitoring commenced 6 hours before the pumping test began in order to gain accurate static water level readings. The pumping rate was manually calculated using a 5 gallon bucket and stop watch, and was re-recorded 16 times throughout the pumping test. The water produced from the pumping test was discharged into a ditch at the side of the highway, roughly 5 m northwest of the bedrock well, and 15 m northwest of the shallow well.

4.3 Aqueous Geochemical Analysis

Groundwater samples from the shallow and deep wells were collected in 2005, 2006 and 2007. As coal was encountered during drilling, one of the objectives of the deep well's pumping test was to acquire a water sample that was representative of the groundwater associated with the coal. Thus, the pump intake was placed at roughly 135 m bgs in order to sample the water as close as possible to the coal seams. It was hypothesized that the water located at the same depth and in direct contact with the coal would provide aqueous geochemical values most representative of the coal seams. Groundwater in the deep bedrock well was sampled after 1 min, 5 min and 60 min of pumping in 2005. Subsequently, the BC Ministry of Environment Nanaimo regional office sampled each well once per year in 2006 and 2007. Both wells were sampled and analyzed for aqueous geochemical constituents relating to drinking water quality, hydrocarbons, volatile organic carbons (VOCs) and methane gas dissolved in water.

5 BOREHOLE SUBSURFACE RESULTS

5.1 Drilling Cuttings Description

The borehole lithology log for the deep well is shown in Figure 2. The upper unconsolidated sediments are essentially the same in both the shallow and deep wells. A detailed description of the drill cuttings for both wells is provided by Fisher (2009). Here, only the coal-related lithology and flows are discussed.

Thick sequences of clean sandstone of varying grain sizes characterize the bedrock encountered at Oyster River below 60 m bgs. Occasional increased fractions of siltstone, mudstone and coal occur down to 147 m bgs, the total depth of WTN 83156.

The first coalified rootlets were observed at 70 m bgs hosted in a dark grey, carbonaceous sandy siltstone, a minor fraction of the bedrock at this depth (5%). Significant production of saline water occurred at 135.3 m bgs, coincident with a coal seam. The drilling cuttings showed the bedrock composition at this depth as 50% very hard fine- to medium-grained sandstone, 40% black coaly mudstone, 5% black, dull, dirty, and blocky coal, and 5% carbonaceous sandy siltstone. The width of the coal seam was approximately 2 m, signified by 90% platy, medium grey siltstone and 10% very fine-grained, silty sandstone with traces of coal. Within a further 2 m, however, fine coal dust was seen in the drill returns, along with the production of more salt water. Although only briefly evidenced in the drill cuttings, a second lower coal seam was penetrated at 138.5 m bgs.

Based on the thick sandstone, minor siltstone and coal, the Dunsmuir Member, the uppermost member of the Comox Formation, is interpreted for this sequence. The Comox X, X Lower, Y, and Y Lower coal seams have been identified based on situation within the coalfield and stratigraphic relationship with the overlying sediments (Bickford *et al*., 1990; Cathyl-Bickford, 2001, 2005; Fisher, 2009). Two water bearing fracture zones were encountered within what is interpreted as the Dunsmuir Member, at approximate depths of 97.5 m and 135.3 m bgs. The lowermost fracture zone was coincident with the Comox Y and Y Lower coal seams, which combined span a total bedrock aquifer thickness of 3 m.

5.2 Borehole Geophysical Analysis

The natural gamma ray and density borehole geophysical logs were particularly useful in correlating with drilling notes in the identification of transitions in grain size dominance, such as differentiating between sandstone and mudstone or coal. The water-bearing fracture zone encountered at 135 m bgs is thought to span a vertical thickness of 3 m and include two thin coal seams noticed in the drilling logs at 135.6 m and 138.4 m bgs. Relatively low gamma ray values are recorded between 134.5 m and 136.5 m bgs, ranging between 45 CPS and 60 CPS; however, within this interval there is a noticeable high of 68 CPS at 135.6 m bgs corresponding to the upper of the two coal seams. Further correlation is a relatively low density recording at 135.6 m bgs, approximately 2.5 g/cc. Immediately below this, between 135.7 m and 136.3 m bgs, there is a brief interval of significantly elevated density, up to 2.65 g/cc. The variation in density between 135.6 m and 136.3 m bgs is interpreted to reflect the density difference between the mudstone and coal seam and the fine- to medium-grained sandstone. Gamma ray values are also somewhat elevated at 138.4 m bgs, corresponding to the lowermost coal seam intercepted at Oyster River; however, there is no significant variation observed in the density log at this depth.

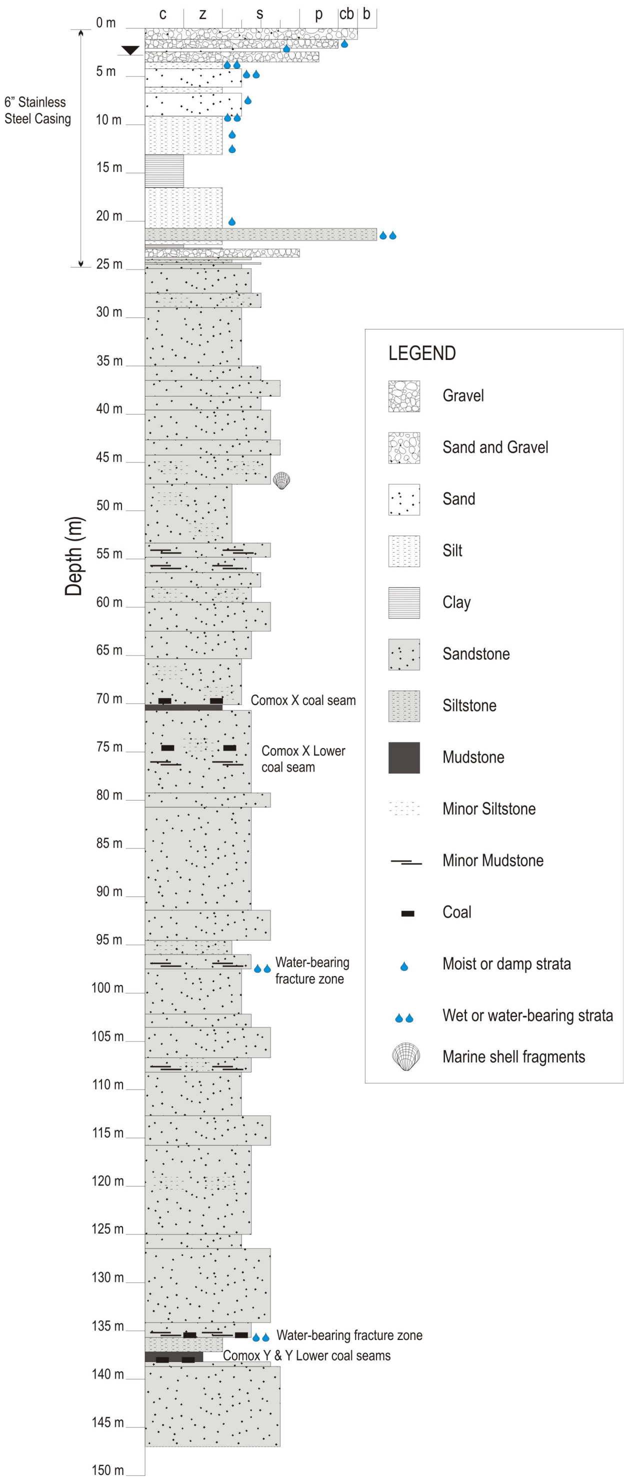

Figure 2. Lithostratigraphic Log for WTN 83156 (Cathyl-Bickford, 2005; Fisher, 2009).

5.3 Groundwater Pumping and Recovery Test Analysis

The 80-minute pumping test in the deep bedrock drew down the water level 80.36 m (Figure 3). The water level

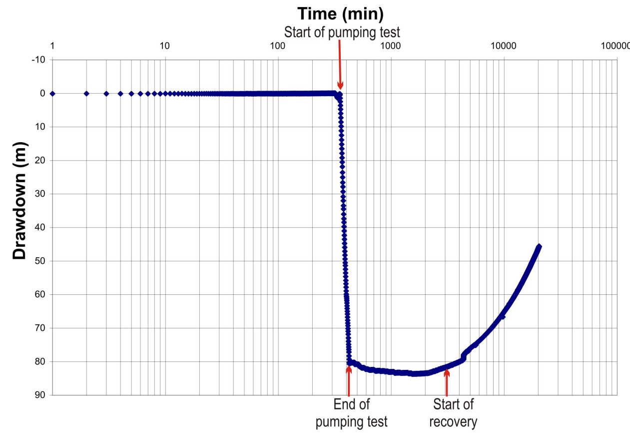

Figure 3. WTN 83156 pumping and recovery test, June 22, 2005 Oyster River, Vancouver Island, BC (Fisher, 2009).

continued to lower by an additional 3.07 m over a period of 18.9 hours following the termination of pumping. This is an unusual response in that the drawdown in the well continued to decrease for close to one day after the pump had been turned off. Thus, interpretation of the data proved difficult, as discussed below. Over the course of the following 36 hours, the water level recovered to the same elevation as at the time the pumping stopped. At the conclusion of the 14 day test the water level had risen to an elevation of 72.92 m +MSL, approximately 43 m below the original static water level. The fact that full recovery was not achieved, even after 14 days, attests to the low storage and hydraulic properties of the aquifer.

Analysis of the pumping test data revealed that the pumping test was affected by significant wellbore storage. Wellbore storage is typically characterized by a slope of one log cycle change in drawdown over one log cycle change in time during pumping. In addition, the pumping rate decreased over time due to the fact that the pumping rate was initially too high and the water level in the well dropped too quickly to maintain the pumping rate. Thus, the overall effect on the pumping test data was the combined effect of wellbore storage and changing pumping rates, making the pumping test data un-usable for determining the hydraulic properties of the aquifer. Consequently, only the recovery test data could be used for analysis, with the limitation that the analytical method used may not be entirely suitable.

The Theis recovery method (Theis, 1935) was employed to estimate the transmissivity (T) and hydraulic conductivity (K) for the confined, fractured bedrock aquifer penetrated by WTN 83156. The method has some general assumptions, some of which are violated in this particular study. The most important assumptions are:

1. The aquifer must be confined, homogeneous and isotropic. This assumption is technically violated because while the aquifer may be confined and isotropic, it is not homogeneous, as fracture zones are encountered along the length of the open borehole. Nevertheless, the Theis recovery

method has been used in other studies under similar hydrogeological conditions (Allen, 1999).

2. There should be no borehole storage (that is, the aquifer should respond to pumping by taking water out of storage within the aquifer and not from the borehole itself). This condition was clearly violated, and it is unclear what effect this might have on the results.
3. The well must be pumped at a constant rate. This was clearly not the case for this test. However, it is possible to take an average of the pumping rate and set this value for analysis of the recovery data (Neville, 2006). Even if the average pumping rate is used, it is not clear what effect this will have on the results.
4. The well must fully recover to its original level. This did not occur, and it is unclear what effect this will have on the results.

For the analysis, the lowest water level attained during the test was used (Figure 3); thus, the recovery period began at 1,213 minutes after the start of the pumping test. Transmissivity, T, was estimated by the Theis recovery method at 7.06 x 10^{-7} m^2/s based on the final recovery trend, $\Delta s_3'$ = 60 m (Figure 4). Hydraulic conductivity, K, was estimated assuming that the width of the fracture zone was equal to the aquifer thickness (3 m) and was estimated at 2.29 x 10^{-7} m/s. Typically, however, the entire open-hole fractured bedrock sequence is considered the aquifer, as opposed to the individual fracture zones identified during drilling (Surrette and Allen, 2008). Therefore, if the entire open-hole bedrock sequence encountered at Oyster River is taken for the aquifer thickness, an interval of 123 m, the calculated conductivity is 5.79 x 10^{-9} m/s. Aquifer storativity cannot be estimated using the Theis recovery method.

Specific and long-term well capacities are difficult to approximate for the bedrock well due to the decline in pumping rate over time. Specific capacity calculations for mid (50 min) and late (70 min) pumping times give values of 5.31 x 10^{-3} L/s/m and 3.02 x 10^{-3} L/s/m, respectively. Late time estimates reveal significantly more consistent and conservative values in comparison to the early time (1 min) estimate of 1.36 x 10^{-1} L/s/m, suggesting that the drawdown may have begun to equilibrate with the lower pumping rates at later time. Early time pumping illustrates significant wellbore storage effects and thus exaggerated specific capacity estimates. Thus, the best estimate for specific capacity is that obtained from late time data: 3.02 x 10^{-3} L/s/m. Long-term well capacity was calculated by considering 70% of the available drawdown (the water column within the wellbore) multiplied by the specific capacity. Based on the specific capacity at 70 minutes of pumping, a long-term well capacity estimate of 0.28 L/s is calculated.

Spot checks during each of the pumping tests were conducted to monitor the static water levels within the well that was not being pumped at the time. During the pumping test of the shallow well (WTN 83157), the static water level within the deep bedrock well (WTN 83156)

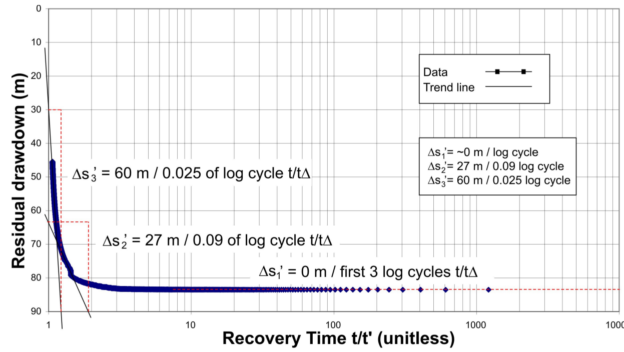

Figure 4. WTN 83156 Theis Recovery Curve (semi-log plot of residual drawdown versus recovery time, t/t' from t = 1213 min, t' = 0 min) (Fisher, 2009).

48.5 m bgs before pumping began, 48.0 m bgs after 73.5 minutes of pumping, and 47.7 m bgs after 4 hours of pumping and 1 hour of recovery. During pumping of the deep bedrock well, the static water level within the shallow surficial well was recorded to be 1.40 m bgs at the start of pumping, and then 1.52 m bgs, 1.45 m bgs, 1.37 m bgs, and 1.38 m bgs throughout the first 30 minutes of pumping.

The pumping and recovery testing at the surficial and bedrock wells at Oyster River provide an initial approximation of the hydraulic properties of stacked surficial and bedrock aquifers. The recovery test of the bedrock well, WTN 83156, approximates the transmissivity and hydraulic conductivity of a fractured bedrock aquifer within the Nanaimo Group sedimentary bedrock sequence. A recent study on Mayne Island, one of the Gulf Islands within the Strait of Georgia, calculated fracture transmissivity values for the Nanaimo Group sedimentary bedrock sequence (Surrette and Allen, 2008). By mapping fracture trace lengths and aperture estimates at outcrop, the study used a stochastic fracture modeling approach to calculate transmissivity values for the fractured bedrock aquifers (Snow, 1968). Surrette and Allen's modeling research resulted in transmissivity values between 7.78 x 10^{-6} m^2/s and 1.74 x 10^{-4} m^2/s (Surrette and Allen, 2008; Allen, 2009). Pumping test data at the well sites estimated transmissivity values in the range of 10^{-6} and 10^{-4} m^2/s, closely matching modeling estimates (Allen, 2009). These values can be compared with 7.06 x 10^{-7} m^2/s, the transmissivity value estimated from the recovery data of the bedrock Oyster River well, WTN 83156. Both the Mayne Island and Oyster River studies approximate similar fracture transmissivity values for the Nanaimo Group sedimentary bedrock sequence. Surrette and Allen (2008) determined that the primary source of groundwater within the Nanaimo Group is by way of interbedded mudstone and sandstone deposits and by fault or fracture zones. Considering the mudstone and coal seams associated with the water-bearing fracture zone identified at 135 m bgs at WTN 83156, it would seem that the hydrogeology of the Nanaimo Group at Oyster River is similar with that of the same bedrock formation at Mayne Island.

Based upon the data collected at Oyster River, hydraulic connection between the two wells is thought to be unlikely. Very little variation in the water levels was noticed at the observation wells, and the variation that was recorded was a slight increase in the static water levels. If the surficial and bedrock aquifers were indeed hydraulically connected, drawdown in the water level of the monitoring well would be expected. The discharge points of the water produced by the pumping tests were approximately 15 m away from the observation wells. Consequently, it is possible that the shallow observation well was affected by the produced water discharged from the deep well recharging the surficial deposits at surface. The hydrostratigraphic nature of surficial unconsolidated sand and gravel suggests that this may be likely. Recharge of the surficial aquifer from discharge at surface is different, however, than subsurface hydraulic communication between the surficial and bedrock aquifers.

A slight increase in the water level of the bedrock well was also noticed during the pumping test of the shallow surficial well. Assuming that the deep well was properly cased and sealed into bedrock, the water produced from pumping the shallow well would have to infiltrate the surficial sediments down to bedrock and then flow through bedrock fractures and into the open-hole bedrock well. For this to occur within 75 min, the time at which a slight increase in static water level was noticed in the bedrock well, is considered unlikely. This, combined with the expectation that the water level in the monitoring well would lower during the pumping test if the aquifers were hydraulically connected, leads to the interpretation that the aquifers are most likely not in hydraulic communication.

5.4 Aqueous Geochemical Analysis

The water of the shallow, unconfined sand aquifer (WTN 83157) is near drinking water quality with respect to the typical ambient water quality parameters with the exception of total iron, which remained above the drinking water threshold (0.3 mg/L) for all three years ranging between 1.41 mg/L and 1.80 mg/L. The concentrations of the VOCs and hydrocarbons present in the shallow well are quite low, between 0.03 µg/L and 0.07 µg/L; therefore, they are considered a low concern with respect to drinking water quality.

As expected, the saline water produced from the deep fractured bedrock aquifer (WTN 83156) is not suitable as a drinking water source. High levels of total dissolved solids, chloride, and sodium exceeded the BC MoE criteria for drinking water for all three years of sampling, with 2005 maximum concentrations of 24,600 mg/L, 12,800 mg/L and 3,860 mg/L, respectively (BC MoE, 2008; Fisher, 2009). Dissolved barium and manganese also exceeded drinking water thresholds for 2005 and 2006 samples. High concentrations of VOCs and hydrocarbons, particularly methane gas (2,123 µg/L), were also found in the first year of sampling. By 2006, however, these constituents were within concentration ranges acceptable of drinking water quality. Relatively high levels of manganese (1,360 µg/L), iron (1.83 mg/L), sulphate (25.7 mg/L) and dissolved methane gas (2,123 µg/L) are indicative of an anoxic aqueous environment.

Aqueous geochemical analysis of WTN 83156 can aid in determining the origin of the high concentration of methane gas found in the 2005 sample. Indicator constituents have been identified to provide a signature concentration relationship common to coalbed methane produced waters throughout North America (Van Voast, 2003). Milliequivalents per litre are used as a relative measure of chemical constituent concentrations and are displayed in Schoeller diagrams (Freeze and Cherry, 1979). Typical geochemical signatures of coalbed methane associated water exhibit high concentrations of sodium (Na), chloride (Cl) and bicarbonate (HCO_3), typically between 10 and 1000 milliequivalents; moderate levels of calcium (Ca) and magnesium (Mg), generally between 1 and 10 milliequivalents; and very low concentrations of sulphate (SO_4), commonly around 0.1 millequivalents (Van Voast, 2003).

The Schoeller diagram (Figure 5, solid line) of the deep bedrock well at Oyster River, WTN 83156, exhibits the general pattern seen in coalbed methane associated waters throughout North America (Van Voast, 2003). The concentrations of most of the key constituents are shown to decrease over the 2 years of monitoring. The concentration of dissolved methane gas significantly decreases over the monitoring period, reducing from 2,123 mg/L in 2005 when the bedrock well was drilled and the thin coal seams first penetrated, through 2006 (29 mg/L) to the latest values of 3.3 mg/L in 2007. The coincident decline of the dissolved methane gas and the key constituents identified to relate with coalbed methane support the interpretation that the water produced from the deep bedrock well at Oyster River is coal related. Furthermore, the significant and relatively rapid decrease in the dissolved methane gas and related constituents in the formation water of the deep well support the concept that the source of the coal related water are the coal seams encountered by the well, which due to their thinness degas over a short amount of time.

Conversely, the Schoeller diagram (Figure 5, dashed line) of the shallow well at Oyster River, WTN 83157, reflects both little change in constituent concentration over time and an entirely different relative concentration pattern. In spite of this, the groundwater produced from the surficial well did contain low concentrations of dissolved methane gas: 0.069 mg/L in 2006 and 0.006 mg/L in 2007. The source of the dissolved methane gas present in the surficial well is hypothesized to be from groundwater produced during the drilling of the deep bedrock well that recharged the surficial aquifer in which the shallow well is completed. Alternatively, given the conservative nature of dissolved chloride and the relatively high and low chloride concentration found in the bedrock and surficial wells, respectively, cross-contamination between the wells may not be the source of the dissolved methane gas in the surficial aquifer. To further assess whether or not the shallow methane gas is associated with coal at depth or produced from recent surficial organic decay, ^{14}C and/or ^{12}C-^{13}C isotopic analysis is recommended.

Following from this correlation, coalbed methane was detected in the fractured bedrock aquifer. The individual coal bed sourcing the methane gas is unclear at this time. The two primary hypotheses at present are: (1) the two

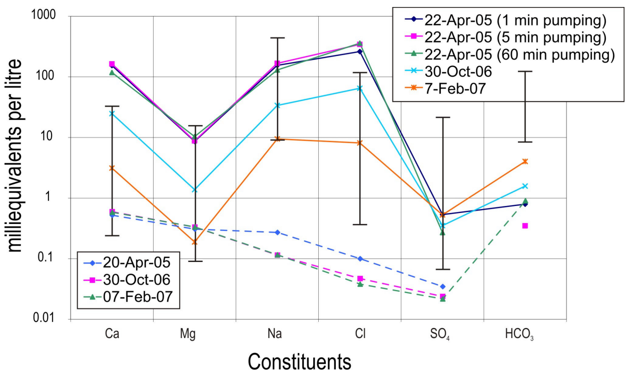

Figure 5. Schoeller diagrams of WTN 83156 (solid line) and WTN 83157 (dashed line) (Fisher, 2009). Schoeller diagrams have been used to identify geochemical signatures for coalbed gas associated groundwater. The vertical black bars are concentration ranges for the noted constituents found in coalbed gas associated groundwater across North America, compiled by Van Voast (2003).

thin coal seams intercepted by the deep well; and, (2) hydraulic and/or gaseous communication with a more distant coal bed through the fracture network of the Nanaimo Group bedrock. Observing the significant decline in dissolved methane concentration between when the well was drilled and the thin coal seams first penetrated in 2005 through to 2007, the former hypothesis comes into favour. If a distant coal bed has been contributing methane to the bedrock groundwater over time, the significant drop in concentration during the well's first year would be unlikely. Therefore, given the data available at present, it can be proposed that the source of the coalbed methane detected in WTN 83156 is the two thin coal seams intercepted at 135 m bgs.

6 CONCLUSIONS

The regional hydrogeology of the Oyster River region of the Comox Coalfield on Vancouver Island, BC, was assessed using drilling logs, borehole geophysics, aqueous geochemistry, pumping and recovery test data, and stratigraphic interpretation of surficial exposures. Coalbed gas potential in the Comox Coalfield occurs mainly between 450 m and 1,500 m depth; however, there is a potential for hydraulic communication between the deeper fractured sedimentary bedrock of the Late Cretaceous Nanaimo Group and the overlying unconsolidated Quaternary aquifers commonly used as community groundwater aquifers. To investigate this, two adjacent groundwater observation wells were drilled; one completed in bedrock (146.9 m) and one in the surficial sediments (7.3 m).

Quaternary sediments, including Vashon Drift and glaciofluvial Capilano Sediments, span 24 m from ground surface to bedrock. Laterally extensive (at least 0.3 km^2) surficial aquifers occur within the upper 10 m. The deep well penetrated the Trent River and Comox Formations of the Nanaimo Group sedimentary bedrock sequence. A water-bearing fracture zone approximately 3 m wide was encountered at 135 m bgs (-5 m +MSL), coincident with the Comox Y and Y Lower coal seams. Dissolved methane gas was detected in both aquifers. Shoeller diagrams reveal that the gas in bedrock is coal related. Fracture transmissivity (T) and hydraulic conductivity (K) for the confined, fractured bedrock aquifer are estimated at 7.06 x 10^{-7} m^2/s and 2.29 x 10^{-7} m/s, respectively, using the Theis recovery method.

A pumping and recovery test in the deep well suggests that it is unlikely there is hydraulic communication between the bedrock and surficial aquifers encountered at Oyster River. This assessment is based on infrequent water level measurements in the shallow well, which did not consistently draw down during pumping of the deeper well. However, the pumping rate was not sustainable for this test and it could not be held constant. As well, there may have been recharge to the shallow aquifer from discharged water. Therefore, another pumping test should be conducted at a lower pumping rate with discharge water directed further away to confirm the potential connection.

The localized study at Oyster River used a multidisciplinary approach to subsurface hydrogeological investigation. Employing various analytical techniques solidified the study's litho- and hydrostratigraphic findings. The data derived from the paired groundwater observation wells contributes to the hydrogeological understanding of both Quaternary sediments and the underlying fractured Nanaimo Group sedimentary bedrock sequence. Additionally, aqueous geochemical analysis correlating the bedrock groundwater with local coal provides initial estimates of coalbed gas produced water for the Comox Coalfield. As interest in the region's groundwater resources and potential for coalbed gas development continue to grow, further research in the area will prove important information for subsurface resource management decisions.

ACKNOWLEDGEMENTS

In response to the need for further hydrogeological baseline data in the Comox Coalfield, a collaborative endeavour was initiated in 2005 between the BC Ministry of Energy, Mines and Petroleum Resources and the BC Ministry of Environment to drill and test three new groundwater observation wells in the central eastern region of Vancouver Island. The innovative and cooperative attitudes of these Ministries have been a great support to this research. Furthermore, without the financial and technical support of the BC Ministry of Energy, Mines and Petroleum Resources, this work could not have been accomplished.

REFERENCES

Abbey, D.G., and Allen, D.M. 2000. Fracture zones, aquifer testing, and scale effects: Considerations in fractured bedrock aquifers of southwestern British Columbia; *Proceedings of the 1st Joint Canadian Geotechnical Society – International Association of*

Hydrogeologists (Canadian National Chapter) CGS-IAH-CNC Groundwater Specialty Conference. 8 pp.

Allen, D.M. 1999. An assessment of the methodologies used for analyzing hydraulic test data in British Columbia. Final Report prepared for Groundwater Section, Water Management Branch, British Columbia Ministry of Environment, Lands and Parks, Victoria, BC. 84 pp.

Allen, D.M. 2009. Nanaimo Group fractured bedrock estimated transmissivity values; pers comm e-mail, January 30, 2009.

Allen, D.M., Liteanu, E., Bishop, T.W., and Mackie, D.C. 2003. Determining the hydraulic properties of fractured bedrock aquifers on the Gulf Islands, British Columbia: Final Report submitted to Ministry of Water, Land and Air Protection, Victoria, BC. 107 pp.

Allen, D.M., Matsuo, G., Suchy, M. and Abbey, D.G. 2001. A Multidisciplinary Approach to Studying the Nature and Occurrence of Saline Groundwater in the Gulf Islands, British Columbia, Canada; *First International Conference on Saltwater Intrusion and Coastal Aquifers – Monitoring, Modeling, and Management*. Essaouira, Morocco. 12 pp.

Allen, D.M. and Suchy, M.S. 2001. Geochemical Evolution of Groundwater on Saturna Island, British Columbia; *Canadian Journal of Earth Sciences* 38: 1059-1080.

B.C. Ministry of Energy, Mines and Petroleum Resources (BC MEMPR). 2005. Comox Coalfield – Baseline Surface Stream Water Quality Survey http://www.em.gov.bc.ca/subwebs/coalbedgas/ERIP/baseline.htm#Vancouver_Island

B.C. Ministry of Environment (BC MoE). 2001. BC Water Resources Atlas. http://www.env.gov.bc.ca/wsd/data_searches/wrbc/index.html

B.C. Ministry of Environment (BC MoE). 2008. Water Quality Guidelines (Criteria) Reports. http://www.env.gov.bc.ca/wat/wq/wq_guidelines.html

Bickford, C.G.C. and Kenyon, C. 1988. Coalfield geology of eastern Vancouver Island (92F); *Geologic Fieldwork 1988*, British Columbia Ministry of Mines and Petroleum Resources, Paper 1988-1: 441-450.

Bickford, C.G.C., Hoffman, G. and Kenyon, C. 1989. Coal measures of the Quinsam area (92F); *Geologic Fieldwork 1988*, British Columbia Ministry of Mines and Petroleum Resources, Paper 1989-1: 559-563.

Bickford, C.G.C., Hoffman, G. and Kenyon, C. 1990. Geological investigations in the coal measures of Oyster River, Mount Washington and Cumberland areas, Vancouver Island (92F/10, 11, 14); *Geologic Fieldwork 1989*, British Columbia Ministry of Mines and Petroleum Resources, Paper 1990-1: 431-437.

Cathyl-Bickford, C.G. 1991. Coal Geology and Coalbed Methane Potential of Comox and Nanaimo Coal Fields, Vancouver Island, British Columbia; Guidebook for the Rocky Mountain Association of Geologists Fall Conference and Field Trip, September 17-20, 1991 Glenwood Springs, Colorado; (ed.) S.D. Schwochow, *Rocky Mountain Association of Geologists*: 155-162.

Cathyl-Bickford, C.G. 2001. Lithostratigraphy of the Comox and Trent River Formations in the Comox Coalfield, Vancouver Island (92F/7, 10, 11, 14); *British Columbia Geological Survey*; GeoFile 2001-1: 1-8.

Cathyl-Bickford, C.G. 2005. Geological completion Report WTN 10104 Province of British Columbia Oyster River test hole No. 1, NTS 92 F/14 Comox Basin (onshore) Vancouver Island, British Columbia, Canada; *Westwater Mining Ltd.*; Report WR 210/1/05.

Earle, S. and Krigh, E. 2004. Geochemistry of Gabriola's groundwater; *Shale* 7: 35-42.

Fisher, G.C. 2009. Hydrogeological Investigation of Quaternary and Late Cretaceous Bedrock Aquifers, Comox Coalfield, Vancouver Island, British Columbia, Canada; M.Sc. Thesis, *University of Victoria*. 215 pp.

Freeze, R.A. and Cherry, J.A. 1979. Groundwater; *Prentice Hall*, Englewood Cliffs, New Jersey. 604 pp.

Fyles, J. G. 1963. Surficial Geology of Horne Lake and Parksville Map-Areas, Vancouver Island, British Columbia 92F/7, 92F/8; *Geological Survey of Canada* Memoir 318, 142 pp.

Jungen, J. 1975. Oyster River, British Columbia – 92F/14 landforms; *BC Ministry of Energy, Mines and Petroleum Resources*: 1:50,000.

Mustard, S.P. 1994. The Upper Cretaceous Nanaimo Group, Georgia Basin; Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H Monger, *Geological Survey of Canada*, Bulletin 481: 27-95.

Nagpal, N.K. 1990. Campbell River Area Oyster River Basin Water Quality Assessment and Objectives Technical Appendix; BC Ministry of Environment, Resource Quality Section, Water Management Branch. 107 pp.

Neville, C.J. 2006. Chapter 7: The Significance and Interpretation of Recovery Data; in Short Course – Interpretation of Pumping Tests In Complex Settings, *7th Joint CGS/IAH-CNC Groundwater Specialty Conference*; October 1, 2006, Vancouver, BC, Canada.

Ryan, B. 2002. Note on Desorption Results of Comox Formation Coals from the Courtenay Area, Vancouver Island, British Columbia; *Geological Fieldwork 2001*, Paper 2002-1.

Ryan, B., Cathyl-Bickford, G., and Neimann, M. 2005. Cumulative Coal Thickness and Coalbed Gas Potential in the Comox Coal Basin, Vancouver Island; in Summary of Activities 2005, *BC Ministry of Energy, Mines and Petroleum Resources*: 157-175.

Snow, D.T. 1986. Rock fracture spacings, openings, and porosities; *Journal of the Soil Mechanics and Foundations Division: Proceedings of the American Society of Civil Engineers* 94: 73-91.

Surrette, M.J. and Allen, D.M. 2008. Quantifying heterogeneity in variably fractured sedimentary rock using a hydrostructural domain; *Geological Society of America Bulletin* 120: 225-237.

Theis, C.V. 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage; *Transactions – American Geophysical Union* 16: 519-524.

Van Voast, W.A. 2003. Geochemical signature of formation waters associated with coalbed methane; *AAPG Bulletin* 87: 667-676.