Investigating the Role of Buried Valley Aquifer Systems in the Regional Hydrogeology of the Peace River Region, Northeastern British Columbia (Parts of NTS 094A, B)

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Introduction

Buried valleys are channel-form depressions, or paleo-valleys, that have been infilled by sediment and buried following their formation (Cummings et al., 2012). Within these buried valleys, permeable material can form thick units that have the potential to store and transmit significant amounts of water, hence the term ‘buried valley aquifers’. Buried valleys have been identified below glaciated terrains in North America and northern Europe, and when filled with permeable sediments, they can represent attractive targets for groundwater exploitation (Shaver and Pusc, 1992; Andriashek, 2000; Cummings et al., 2012; Oldenborger et al., 2013). Studying buried valleys and gaining an understanding of their architecture, lateral extent and the continuity of the permeable units is crucial to managing groundwater resources (Hickin et al., 2016).

Several studies have explored the hydraulic role of buried valley aquifers through both field techniques (e.g., Troost and Curry, 1991; Shaver and Pusc, 1992; van der Kamp and Maathuis, 2012) and numerical modeling (e.g., Shaver and Pusc, 1992; Seifert et al., 2008; Seyoum and Eckstein, 2014). Investigations into buried valley aquifers using numerical modeling have incorporated their geological structure and have explored the continuity of the permeable units within their fill, which are among the key factors that control the effect that buried valleys have on groundwater flow (Russell et al., 2004). These studies, however, tend to be localized (e.g., one buried valley). “At the regional scale, there has been limited investigation of aquifer extent and continuity along buried valleys, the groundwater resource potential of buried valley aquifer systems, and the hydraulic role of buried valleys on regional flow” (Russell, 2004). To examine the resource potential of buried valley aquifers, the impact that buried valleys have on the regional groundwater flow regime must be investigated.

The purpose of this research is to contribute to the knowledge of buried valley aquifer hydrogeology and explore the influence that buried valley aquifers have on groundwater flow at a regional scale. The study area is the Peace River region of northeastern British Columbia (BC). The aim of this work is also to extend the research conducted for Geoscience BC’s Peace Project, a project aimed at contributing new information about the available water resources in northeastern BC.

The specific objectives of the research are to

- determine the nature of the continuity of the permeable units within the buried valley network in the Peace River region,
- characterize the regional groundwater flow system for the buried valley aquifer network, and
- analyze the regional water budget under the influence of the buried valley aquifers and assess the validity of the buried valley aquifers as a water resource.

Study Area

Northeastern BC has seen a large increase in shale gas development during the last 15 years. To access the gas in the tight shale units, industry hydraulically fractures the rock (fracking) to increase its permeability. This fracking requires large volumes of water, with a single well requiring potentially more than 20 000 m^3 of water. Currently, most of the water used for hydraulic fracturing in northeastern BC is surface water; however, increased development may increase the demand for other water sources, specifically groundwater found in northeastern BC’s aquifers.

Keywords: *British Columbia, buried valley aquifers, regional groundwater flow, hydrogeology, Petrel, MODFLOW, SkyTEM, northeastern BC, Peace River region*

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Unconsolidated aquifers that are particularly important to this region are in Neogene (preglacial; existed prior to glaciation) and Quaternary (glacial; cut during glaciation) buried valleys eroded into overlying sediments and/or bedrock. Both types of buried valleys occur in the Peace River region, and the valley-fill material can sometimes contain sand and gravel aquifers (Lowen, 2011), making them appealing targets for groundwater exploration. Most, however, have little to no surface expression because following the deposition of the valley-fill material, processes such as aggradation subsequently buried these valleys (Hickin, 2011; Hickin et al., 2016). This makes the process of identifying and mapping these buried valley aquifers challenging.

In the Peace River region, the approximate extent of a large network of buried valleys has been delineated (Figure 1; Petrel Robertson Consulting Ltd., 2015); however, the hydrogeological characteristics of these buried valleys, in particular the potential continuity of high permeability materials, is largely unknown. Moreover, the broader role that these buried valleys play in the regional groundwater flow regime of the Peace River region has yet to be explored.

Methods

Buried valley geometry is quite complex (Oldenborger et al., 2014); therefore, the incorporation of high-resolution geophysical data is necessary to interpret their architecture. This study will incorporate the geological data and interpretations from two geophysical techniques: electromagnetic surveys and gamma-ray logging.

Airborne Electromagnetic Survey Data

During the last several years, airborne time-domain electromagnetic (TEM) systems have been developed and proven successful for hydrogeophysical studies of buried valleys (e.g., Steuer et al., 2009; Høyer et al., 2011; Oldenborger et al., 2013). As part of Geoscience BC's Peace Project, approximately 21 000 line-kilometres were flown with the SkyTEM system (Sørensen and Auken, 2004) to collect airborne TEM data for the Peace River region. SkyTEM is an airborne TEM system specifically designed for environmental investigations (Sørensen and Auken, 2004). The TEM data were subject to one-dimensional and three-dimensional inversion and are presented as interpreted horizontal subsurface resistivity slices (Figure 2) and vertical resistivity cross sections. Generally, low resistivity is interpreted to represent fine-grained material such as clay or material containing saline water, whereas high resistivity is interpreted to represent coarse-grained material such as sand and gravel or bedrock.

Gamma-Ray Logs

Gamma-ray logs are used to measure the natural radioactivity emitted by sediments. High gamma-ray values generally relate to clays and result from higher concentrations of radioactive elements found in clay minerals, such as uranium, potassium and thorium (Quartero et al., 2014). Low gamma-ray values generally relate to sand and coarse-grained material. Gamma-ray logs are commonly used to determine subsurface lithology and stratigraphy; however, the steel surface casing in the well mutes the gamma-ray response from the formation, reducing the amplitude and variance of the data (Quartero et al., 2014). While surface casing enhances wellbore stability and protects shallow groundwater from surface contamination, the attenuation caused by the casing lowers the overall gamma-ray response and is problematic for geological interpretation (Quartero et al., 2014).

The gamma-ray logs from approximately 1400 wells in the Peace River region have been corrected for the attenuation of the gamma-ray response caused by the surface casing using the statistical correction technique developed by Quartero et al. (2014). This technique allows the cased and noncased log intervals to be merged into one continuous gamma-ray curve for stratigraphic correlation (Figure 3).

Objective 1: Geological Model

The surficial geology map of the Peace Project area in Figure 1 shows the outline of a large buried valley network. This large network will be the focus for this research, thus, the developed geological model will likely be in this area. The exact area of the model will be defined at a later stage in the research, once all available data have been examined.

The geological and geophysical datasets will be imported into the reservoir software, Petrel (Schlumberger Limited, 2011), and used to design a 3-D geological model of the buried valley network. Two options will be explored for the model domain:

- The vertical extent of the geological model will be from ground surface to the top of bedrock. Bedrock topography (from Petrel Robertson Consulting Ltd., 2015) and a digital elevation model (DEM) will be used as the top and bottom surfaces of the geological model, respectively. This geological model and the following hydrogeological model will only consider the unconsolidated sediments. The bedrock will be considered impermeable.
- A full geological model will be generated that includes the bedrock, down to approximately 200 m, below which there is likely limited groundwater flow.

The interpreted geology from the TEM resistivity slices and cross sections will be used to differentiate fine- and coarse-grained material within the valley fill (and possibly

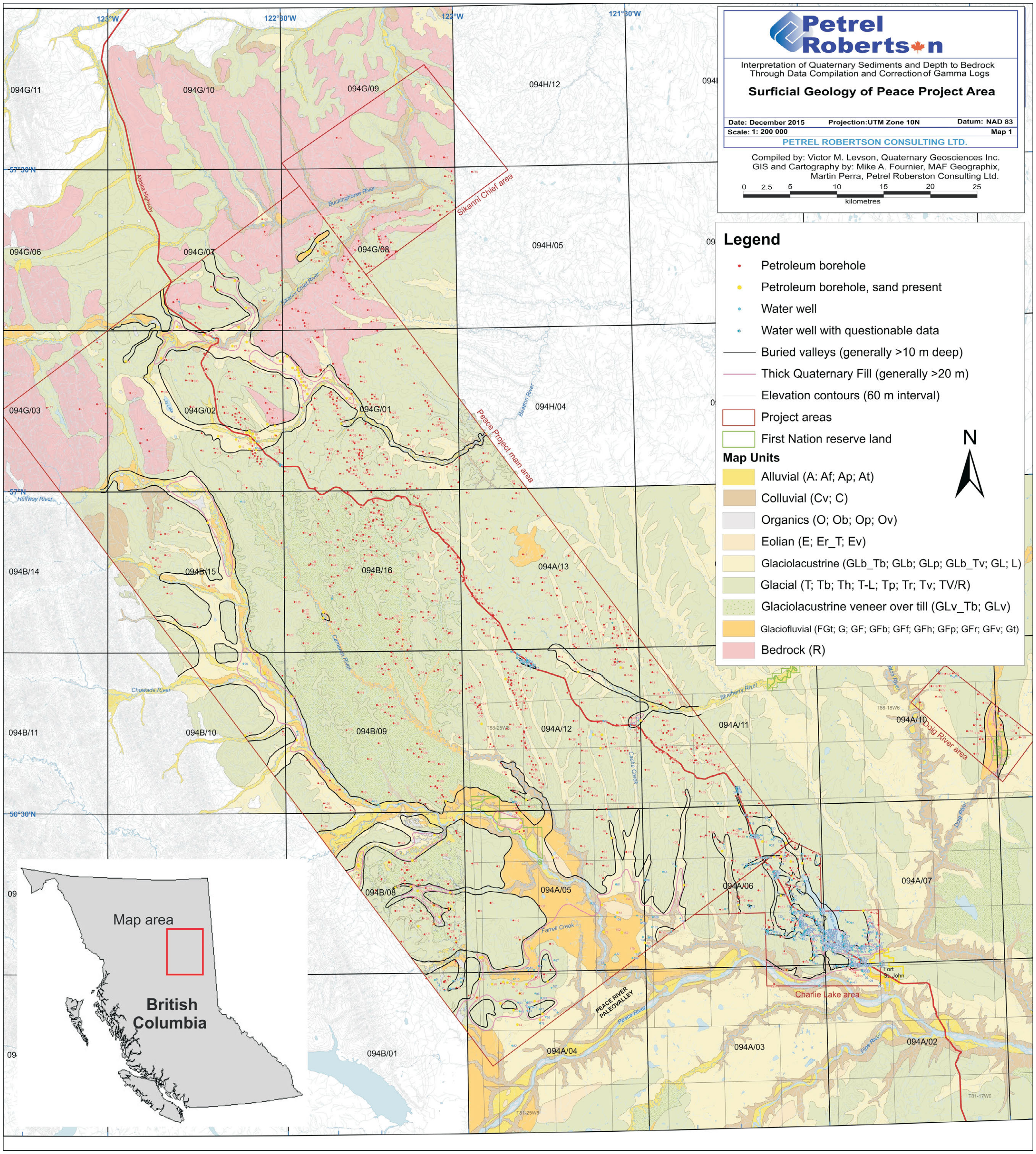

Figure 1. Surficial geology of the Peace Project area in northeastern British Columbia. The outlines of the four main areas within the Peace Project are shown in red (Sikanni Chief, Peace Project Main, Charlie Lake and Doig River). Thick dark lines represent outlines of buried valleys (generally >10 m deep). Modified from Petrel Robertson Consulting Ltd. (2015).

lithological differences in bedrock) and, in combination with bedrock topography, to visualize the structure of the buried valleys themselves. The surficial geology map, available gamma-ray logs for oil and gas wells, and lithology logs reported by well drillers (from the WELLS database; BC Ministry of Environment, 2016) will supplement the TEM data to help confirm the depth to bedrock and verify the geological interpretation from the TEM data. There is also a possibility that a few targeted boreholes will be drilled in the study area to confirm the geological interpretation of the geophysical data. The information collected from these boreholes would be included in the study.

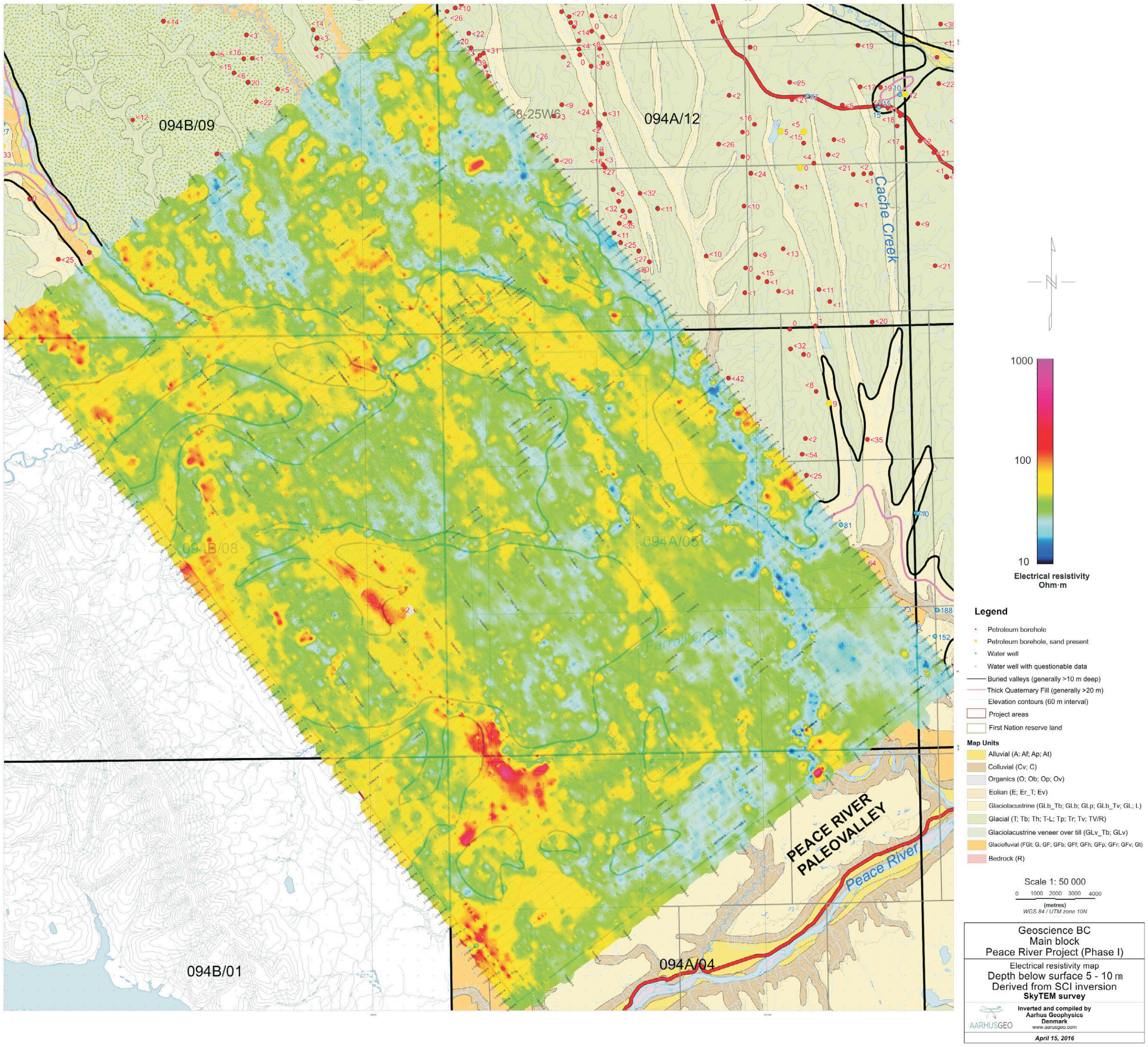

Figure 2. Example of a horizontal subsurface resistivity slice showing interpreted resistivity distribution from 5 to 10 m below ground surface in the Peace Project Main area of the Peace Project. Resistivity distribution was derived from spatially constrained inversion (SCI). Depth to bedrock in metres is shown next to the petroleum and water wells in the figure. Modified from Aarhus Geophysics ApS (2016).

The hydraulic properties of the geological units will be estimated primarily from the literature based on the texture of the Quaternary deposits in the Peace River region. These will be supplemented by estimates obtained from pumping tests and possibly grain size data. Based on distinct hydraulic conductivity contrasts between the dominant material types (e.g., till versus glaciofluvial), unique hydrostratigraphic units will be defined.

Objective 2: Numerical Groundwater Flow Model

Characterizing a groundwater flow system requires a geological model, defined recharge areas and amounts of recharge, delineation of flow paths and the volume of flow, and defined discharge areas. Numerical groundwater flow models are valuable tools for characterizing groundwater flow systems. The most commonly used groundwater flow model is MODFLOW, and since its release in 1988, it has become the industry standard for numerical groundwater modeling (Zhou and Li, 2011). MODFLOW is a block-centred, finite-difference code that can handle complex boundaries and spatial and temporal variations of the system (Pisinaras et al., 2007). MODFLOW can also import geological models generated in other programs, such as Petrel (Schlumberger Limited, 2011).

Using the 3-D geological model developed in Objective 1, an interpretive, steady-state, 3-D numerical groundwater flow model will be created for the Peace River study area to characterize the regional groundwater flow system of the buried valley network. The model boundary conditions are uncertain, but will be approximated based on existing information. Spatial recharge has been estimated for the Peace River region by Holding and Allen (2015), who provide a range of average mean annual recharge between 88 and 1006 mm/year. Based on the model location and the spatial distribution of recharge from Holding and Allen (2015), recharge rates within the range of 0 and 300 mm/year will be tested and applied to the top surface of the numerical model. Other boundary conditions thought to control the flow within the buried valley aquifer system will be investigated prior to model construction. These may include major rivers, such as the Peace River, and other water bodies. Available hydrometric data will be used where rating curves are available (to obtain the river stage from discharge measurements).

The Particle Tracking tool in MODFLOW will be used to identify and delineate likely recharge and discharge areas of the buried valley aquifer network. The groundwater travel paths will also be observed to explore the regional groundwater flow system and investigate the hydraulic gradient.

Objective 3: Regional Water Budget

In MODFLOW, the Zone Budget analysis tool will be used to quantify the amount of recharge to and discharge from the buried valleys, respectively, and to estimate how much water is moving through the buried valley aquifer network. If the model domain includes bedrock, the Zone Budget tool will also be used to estimate how much water is moving outside the buried valleys in the bedrock. This amount will be compared with the amount of flow within the buried valley network to address the question of the impact of buried valley aquifers on regional groundwater flow.

Additionally within the numerical model, simulations will be carried out to assess the potential of these buried valley aquifers as a long-term, sustainable groundwater resource. This will be achieved through adding to the steady-state model pumping wells that are completed in the buried valley aquifers. Abstraction will be simulated, and the Particle Tracking tool will be used identify capture zones in the steady-state flow field.

Future Work

Objective 1 is currently underway for this project. The geological and geophysical data will be brought into Petrel (Schlumberger Limited, 2011), and these datasets will be used to design the geological model of the buried valley network in the Peace River study area. Based on the developed geological model, a numerical groundwater flow model will be constructed for the study area. This flow model will be used to assess the impact of buried valley aquifers on regional groundwater flow. It is hoped that the

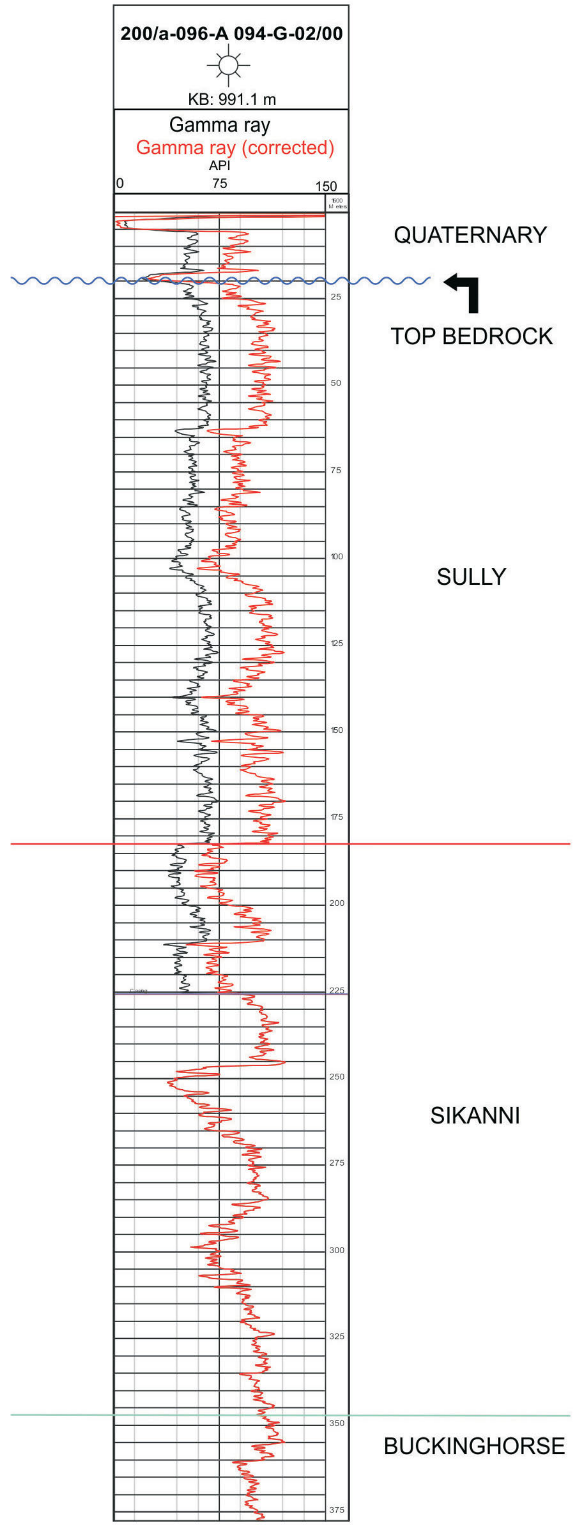

Figure 3. Example of a gamma-ray log from the Peace Project area corrected using the Quartero et al. (2014) method. The gamma-ray curve from the cased-hole interval is shown in black and the corrected gamma-ray curve is shown in red. Stratigraphic picks are also shown on the gamma-ray log, beginning with the youngest: Quaternary sediments, Upper Cretaceous Sully Formation, Lower Cretaceous Sikanni Formation and Lower Cretaceous Buckinghorse Formation. Modified from Petrel Robertson Consulting Ltd. (2015).

results of this study can provide insight to future investigations of regional groundwater systems containing buried valleys. This research will be completed and documented as an M.Sc. thesis.

References

Aarhus Geophysics ApS (2016): Processing and inversion of SkyTEM data, Peace River main area – phase 1; Geoscience BC, Report 2016-09a, 28 p, URL <http://www.geosciencebc.com/s/Report2016-09.asp> [December 2016].

Andriashek, L.D. (2000): Quaternary stratigraphy of the buried Birch and Willow bedrock channels, NE Alberta; Alberta Energy and Utilities Board, EUB/AGS Earth Sciences, Report 2000-15, 61 p.

BC Ministry of Environment (2016): WELLS database; BC Ministry of Environment, URL <https://a100.gov.bc.ca/pub/wells/public/indexreports.jsp> [November 2016].

Cummings, D.I., Russell, H.A.J. and Sharpe, D.R. (2012): Buried-valley aquifers in the Canadian prairies: geology, hydrogeology, and origin; Canadian Journal of Earth Sciences, v. 49, no. 9, p. 987–1004.

Hickin, A.S. (2011): Preliminary bedrock topography and drift thickness of the Montney Play area; BC Ministry of Energy and Mines, BC Geological Survey, Open File 2011-1 and Geoscience BC, Report 2011-07, 2 maps, 1:500 000 scale, URL <http://www.geosciencebc.com/s/Report2011-07.asp> [November 2016].

Hickin, A.S., Best, M.E. and Pugin, A. (2016): Geometry and valley-fill stratigraphic framework for aquifers in the Groundbirch paleovalley assessed through shallow seismic and ground-based electromagnetic surveys; BC Ministry of Energy and Mines, BC Geological Survey, Open File 2016-05, 46 p., URL <http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/OpenFiles/2016/Pages/2016-5.aspx> [November 2016].

Holding, S. and Allen, D.M. (2015): Shallow groundwater intrinsic vulnerability mapping in northeast British Columbia; Simon Fraser University, Final report prepared for Pacific Institute for Climate Solutions and BC Ministry of Energy and Mines, 41 p., URL <http://pics.uvic.ca/sites/default/files/uploads/publications/NEBC%20DRASTIC%20Report_Final.pdf> [November 2016].

Høyer, A., Lykke-Andersen, H., Jørgensen, F. and Auken, E. (2011): Combined interpretation of SkyTEM and high-resolution seismic data; Physics and Chemistry of the Earth, Parts A/B/C, v. 36, no. 16, p. 1386–1397.

Lowen, D. (2011): Aquifer classification mapping in the Peace River region for the Montney water project; *in* EcoCat: the ecological reports catalogue, BC Ministry of Environment, Report 23 247, 51 p.

Oldenborger, G.A., Logan, C.E., Hinton, M.J., Sapia, V., Pugin, A.J.M., Sharpe, D.R., Calderhead, A.I. and Russell, H.A.J. (2014): 3D hydrogeological model building using airborne electromagnetic data; Near Surface Geoscience 2014, 20th European Meeting of Environmental and Engineering Geophysics, Athens, Greece, September 14–18, 2014, 5 p.

Oldenborger, G.A., Pugin, A.J.M. and Pullan, S.E. (2013): Airborne time-domain electromagnetics, electrical resistivity and seismic reflection for regional three-dimensional mapping and characterization of the Spiritwood Valley aquifer, Manitoba, Canada; Near Surface Geophysics, v. 11, no. 1, p. 63–74.

Petrel Robertson Consulting Ltd. (2015): Interpretation of Quaternary sediments and depth to bedrock through data compilation and correction of gamma logs; Geoscience BC, Report 2016-04, 24 p., URL <http://www.geosciencebc.com/s/Report2016-04.asp> [November 2016].

Pisinaras, V., Petalas, C., Tsihrintzis, V. and Zagana, E. (2007): A groundwater flow model for water resources management in the Ismarida plain, North Greece; Environmental Modeling and Assessment, v. 12, no. 2, p. 75–89.

Quartero, E., Bechtel, D., Leier, A. and Bentley, L. (2014): Gamma-ray normalization of shallow well-log data with applications to the Paleocene Paskapoo formation, Alberta; Canadian Journal of Earth Sciences, v. 51, no. 5, p. 452–465.

Russell, H.A.J., Hinton, M.J., van der Kamp, G. and Sharpe, D.R. (2004): An overview of the architecture, sedimentology and hydrogeology of buried-valley aquifers in Canada; *in* Proceedings of the 57th Geotechnical Conference and the 5th Joint CGS-IAH Conference, Québec, Quebec, October 24–27, 2004, p. 2B (26–33), doi:10.4095/215602

Schlumberger Limited (2011): Petrel 2011 for Windows; Schlumberger Limited, online help (not available in libraries).

Seifert, D., Sonnenborg, T.O., Scharling, P. and Hinsby, K. (2008): Use of alternative conceptual models to assess the impact of a buried valley on groundwater vulnerability; Hydrogeology Journal, v. 16, no. 4, p. 659–674.

Seyoum, W.M. and Eckstein, Y. (2014): Hydraulic relationships between buried valley sediments of the glacial drift and adjacent bedrock formations in northeastern Ohio, USA; Hydrogeology Journal, v. 22, no. 5, p. 1193–1206.

Shaver, R.B. and Pusc, S.W. (1992): Hydraulic barriers in Pleistocene buried-valley aquifers; Ground Water, v. 30, no. 1, p. 21–28.

Sørensen, K.I. and Auken, E. (2004): SkyTEM–a new high-resolution helicopter transient electromagnetic system; Exploration Geophysics, v. 35, no. 3, p. 194–202.

Steuer, A., Siemon, B. and Auken, E. (2009): A comparison of helicopter-borne electromagnetics in frequency- and time-domain at the Cuxhaven valley in Northern Germany; Journal of Applied Geophysics, v. 67, no. 3, p. 194–205.

Troost, K.G. and Curry, B.B. (1991): Genesis and continuity of Quaternary sand and gravel in glaciogenic sediment at a proposed low-level radioactive waste disposal site in East-Central Illinois; Environmental Geology and Water Sciences, v. 18, no. 3, p. 159–170.

van der Kamp, G. and Maathuis, H. (2012): The unusual and large drawdown response of buried-valley aquifers to pumping; Ground Water, v. 50, no. 2, p. 207–215.

Zhou, Y. and Li, W. (2011): A review of regional groundwater flow modeling; Geoscience Frontiers, v. 2, no. 2, p. 205–214.