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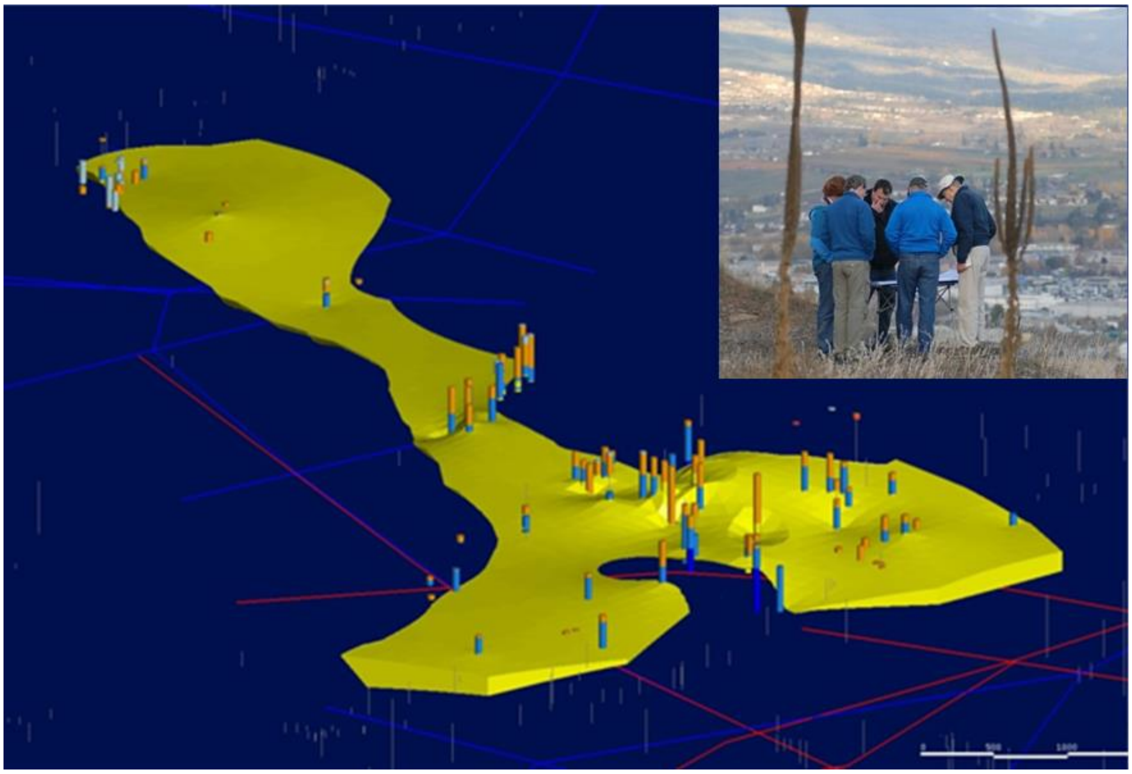
North Okanagan Aquifer Mapping and Geologic Modelling: Summary of Results and 3D Interpretation

Martin Stewart and Remi Allard



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Cover Photographs:
Stewart, M.L., 2017. Digital rendering of the O'Keefe Confined Aquifer, looking north; inset: Dr. Nichol, D. Thomson, S. Thomson, R. Allard and R. Fulton (left to right) discussing glacial history overlooking Vernon to the east, from Turtle Mountain.

Acknowledgements

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EXECUTIVE SUMMARY

This report presents the results of a focused assessment of the hydrostratigraphy of the northern portion of the Okanagan Basin, extending from Vernon, northwest to Salmon Arm, and north to Mara Lake. Groundwater is significantly used for domestic, agricultural, and municipal water supply in the north Okanagan, and demand is expected to rise. Groundwater is the only available source to meet that growth in demand. This assessment seeks to improve the understanding of the geologic history and the physical hydrogeology of the aquifers which contain most of the accessible groundwater in the region.

Surficial geology of the Okanagan Basin has been the focus of numerous studies and several scientific articles. In this area, uncertainty still exists regarding the Quaternary stratigraphy and the relationship with aquifers. The main objective of this study was to compare the historical aquifer mapping by the British Columbia Ministry of Environment and Climate Change Strategy (B.C. ENV) with geological units derived by other studies to establish updated aquifer boundaries within the study area. This was accomplished through the development of a 3-dimensional (3-D) overburden geological model (using LeapfrogTM software) to identify hydrostratigraphic units that in turn were used to establish the updated aquifers. The model was used to re-characterize the reconciled aquifers using the B.C. Aquifer Classification system, prepare a well summary spreadsheet correlating all wells to the reconciled aquifers, and to identify data gaps.

The scale and scope of this assessment were sufficient for delineating broad hydrostratigraphic trends. The aquifer assemblages have been refined in many of the valleys where the scale of the aquifer extent versus aquifer thickness, and quantity of data were sufficient. Despite having an apparently complex geologic history, the Quaternary geology of the North Okanagan is remarkably consistent within valleys of similar size and geometry. Three basic valley types with characteristic hydrostratigraphy and aquifer geometry have been identified, including MAIN (Okanagan, Lower Salmon River), SECONDARY (O'Keefe, Hullcar and Tuhok) and TERTIARY (Ashton Creek, BX Creek, and lesser) valleys.

The MAIN valleys host shallow unconfined and confined aquifers limited to depths of between 10 to 100 m bgs (metres below ground surface), which support most the local groundwater supply needs. These shallow aquifers are found throughout much of the MAIN valleys and originate from either: pre-glacial alluvium, or late to post-glacial kame, outwash and alluvium. Thus, the current aquifers mapped by the B.C. ENV in the Okanagan Valley were determined to be stratigraphically semi-continuous and of similar provenance. This assessment recommends that connectivity of the Okanagan Valley aquifers is recognized and considered in management of groundwater resources in the area, but that current aquifer boundaries are retained with modest revisions. At least two deeper aquifers were also identified in a limited number of boreholes in the Okanagan Valley. The extent of the deeper aquifers is uncertain; the origins of these aquifers is discussed in Nichol et al (2015). The Salmon River aquifers may be connected to equivalent aquifers upstream of the project area, however, downstream they appear to grade into finer grained formations below Salmon Arm.

The SECONDARY valleys of O'Keefe, Hullcar and Tuhok host thicker and coarser-grained aquifers in comparison to the MAIN valleys. These valleys hosted significantly higher energy depositional environments during formation of the aquifers in comparison to the MAIN valleys. However, the overall assemblage is roughly the same. Unconfined, semi-confined and confined aquifers at shallow depths supply most of the local groundwater needs for the residents and communities of the secondary valleys. The confined aquifers comprise thick accumulations of in situ and reworked pre-glacial alluvium, while the unconfined aquifers are dominantly composed of late glacial outwash and kame deposits. The shallow unconfined aquifers in these valleys are attributed to the periodic sudden release of meltwater and sediment that built up behind ice blockages to the west in the Lower Salmon River Valley during the

late stages of the Fraser Glaciation. These same flooding events are interpreted to have formed large alluvial fans at the lower outlet of the SECONDARY valleys, where they enter the Okanagan Valley, but are currently only preserved below the Grandview Flats and Sleepy Hollow areas.

The TERTIARY valleys of Ashton Creek, BX Creek and numerous lesser valleys adjacent to the Okanagan Valley have provided a consistent, significant source of alluvial sediments deposited semi-continuously from prior to the Fraser glaciation, through to the present. These areas host deeply incised creek channels fed by local surface water catchments on steep hill slopes. Historically, these creeks have carried sediment downslope, depositing it as alluvial fans where they intersect shallower slopes of the Okanagan Valley. These alluvial fans form some of the most productive aquifers in the region, and provide important sources of recharge to adjacent confined aquifers.

In the Okanagan Valley, the alluvial fan deposits are gradational with Kame deposits (of similar provenance, but of glacial origin), the combination of which make up the Okanagan Valley unconfined aquifers. At Eagle Rock and Mara Lake, alluvial deposits are of sufficient thickness and extent that they are distinguished as subdivisions of the larger aquifer, although they are likely of similar provenance and are physically connected to the Okanagan Valley aquifers. Stratigraphy of the Mara Lake and Eagle Rock aquifers is relatively homogeneous from the bedrock contact, vertically to surface. Any intervening confining unit is thin or absent, resulting in strong vertical hydraulic connection within the aquifer. These strata span the same period that saw the formation of the complex interlayered assemblage of aquifers and aquitards composing the Okanagan Aquifers. Therefore, despite being of uniform hydrostratigraphy, the Eagle Rock and Mara Lake aquifers comprise multiple sequences of sedimentation which are laterally equivalent with, and hydraulically connected to, multiple distinct aquifers in the Okanagan valley.

Near the town of Ashton Creek, four fans, including two pre-glacial and two late to post-glacial fans, originating from the Ashton Creek Valley and from the Brash Creek Valley, are amalgamated into two relatively continuous aquifers below the Shuswap River Valley. The first aquifer, the Ashton Creek confined aquifer, blankets the northern slope of the valley at the base of the valley overburden, and may be composed of both alluvial fan and colluvial deposits. The second aquifer lies sub-horizontally just below the ground surface, and is separated from the first aquifer by a confining unit of probable glacial origin. This unit is better delineated by borehole logs, and clearly highlights the geometry of overlapping fans developed below the outlet of the two creeks.

In the headwaters of BX Creek, a similar aquifer to the Ashton Creek confined aquifer blankets the northern bedrock slope of the valley, below a confining till layer. These deposits may be correlated with fan sediments comprising the Okanagan Valley confined and unconfined aquifers at the foot of BX Creek below Vernon. However, the two are unlikely to be hydraulically well-connected due to a narrowing of BX Creek above Vernon, and the significant difference in elevation between the BX Creek headwaters and the Vernon area.

Uncertainty remains following this assessment, specifically relating to the degree of vertical hydraulic connection between aquifers. The uncertainty stems from the sparse nature of borehole data and inadequate information regarding the hydraulic conductivity of aquifer, non-aquifer, and confining strata. The 3-D geological models of the Okanagan Valley, Lower Salmon River Valley and Tuhok Valley require additional work to be more inclusive of existing borehole data, and to refine interpretations at smaller scales.

In areas of higher interest with respect to water management and water use, wellhead surveys are recommended to verify the location of boreholes in key locations. An initial study of the existing water level database should be conducted in the context of the revised 3D aquifer geology models to assess the limits of saturated aquifer sediments, and define hydraulic gradients and piezometric relationships between aquifers. A detailed field study of water levels in surveyed wells in areas of interest will be required to sufficiently explore the extent of saturated aquifer and hydraulic gradients in the region. A detailed field study would include measurement of water levels in key wells over a short period of time; once during the low level of the year (fall) and again during peak levels (spring freshet). Assessment of long-term monitoring data from observation wells are recommended to aid in characterization of the aquifers, and transient hydraulic gradients within them. The digital files provided to the B.C. ENV as a deliverable for this assignment provide insight into the relationships between the major aquifers mapped in the region through previous studies. Descriptions and conclusions provided in this report bridge the gap between analysis of hydrostratigraphic relationships and the current understanding of the glacial history of the region. Collectively, this compilation represents an improved foundation for managing groundwater resources in the region and provides a basis for additional future work.

CONTENTS

1. BACKGROUND

Although numerous studies of the geology of the Okanagan Basin have been completed, considerable disparity remains regarding the Quaternary stratigraphy in the area. Naismith (1962) was the first to complete regional surface mapping and to develop a regional stratigraphic framework for the Okanagan. Fulton (1975) subsequently re-mapped the surficial materials and stratigraphy and derived a history of glacial advance and recession for the area. He identified at least two glacial episodes in the Interior of British Columbia. Additional studies of the stratigraphy and glacial history were completed by Lowden et al. (1967), Fulton (1968, 1969, 1972, 1975), and Fulton & Smith (1978).

The British Columbia Ministry of Environment & Climate Change Strategy (B.C. ENV) aquifer database, which has information on more than 1,100 aquifers, has been successfully used for over twenty years to help the B.C. ENV set priorities for the assessment and monitoring of aquifers. The library of information developed to date presents a basis for water managers and allocation staff to support goals of the Water Sustainability Act (WSA); however, the B.C. ENV has identified that more detailed aquifer characterization studies are needed to effectively manage groundwater resources in priority areas such as the northern Okanagan Basin (B.C. ENV, 2012). Detailed characterization of hydrostratigraphy constitutes the first step necessary to understand groundwater availability and hydraulic connectivity with valued aquatic habitats (B.C. ENV, 2012). This foundation is crucial for the design of further studies to characterize groundwater quantity and quality, and the role of groundwater discharge in sustaining ecosystem health.

This assessment is focussed on studying aquifers in the northern portion of the Okanagan Basin, extending from Vernon northwest to Salmon Arm and north to Mara Lake (Figure 1). Groundwater is significantly used for domestic, agricultural, and municipal water supply in this region. Demand for water is expected to rise with increasing population. Agricultural growth will also result in a greater demand for water. As surface water licensing is, for the most part, fully allocated in the area, groundwater demand will increase. There is also uncertainty regarding the impacts of drought and long-term climate change on the sustainability of recharge to aquifers.

Recent hydrogeological studies by Golder et al. (2009), Ping et al. (2010), Smerdon et al. (2008) and Nichol et al. (2015) have provided more information regarding the hydrogeology in the area. The most recent study in the area was commissioned by a collaborative B.C. government inter-ministry working group, and focuses on water quality in the Hullcar Aquifer (Golder, 2017).

Glacial history, surficial and bedrock geology, and tectonic history have significantly influenced the distribution and characteristics of aquifers in the region, and in turn the availability and productivity of aquifers in the area. Management and protection of the groundwater resources in the North Okanagan Basin will benefit substantially from a better understanding of the three-dimensional (3D) extent, characteristics and relationships of aquifers in the area. The results of this study will be used to focus and inform further work which could include, but would not be limited to: water budgets, hydraulic interaction between aquifers and with surface water bodies, and intrinsic aquifer vulnerability.

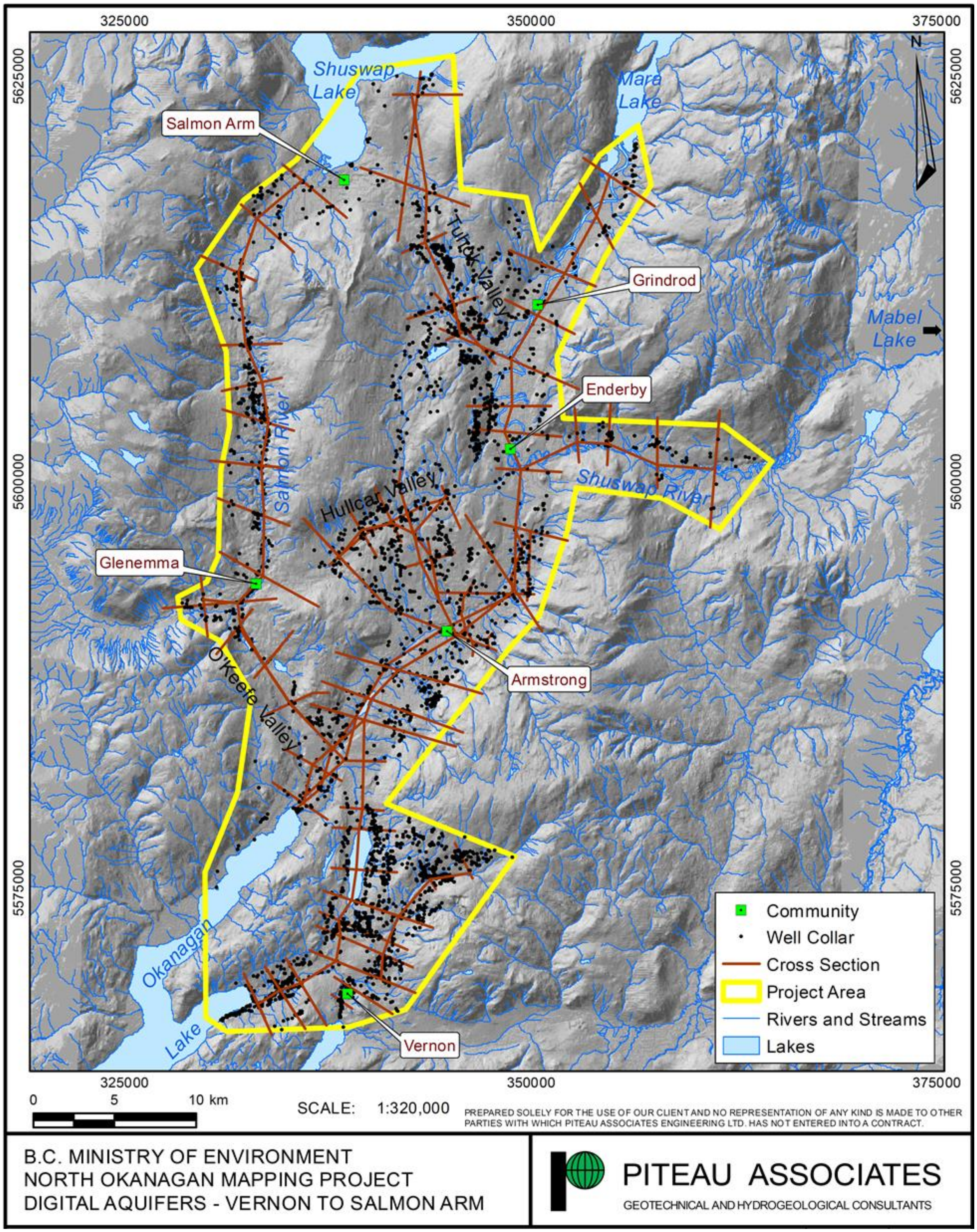

Figure 1: Study area and borehole locations.

1.1 Objectives

The objective of this work is to provide a single comprehensive study that synthesizes the hydrostratigraphic information available for the North Okanagan Basin to produce a rigorous and defensible geologic model. This geologic model is intended to provide a foundation both for future groundwater allocation decisions and for future regional or site specific hydrogeologic studies. The components of this study area as follows:

- gather and summarize all relevant data available for the study area;
- identify key stratigraphic units/sequences;
- correlate all non-bedrock wells in the study area to specific units/sequences;
- compare historical aquifer mapping by the B.C. ENV with geological units derived in more recent studies to derive updated aquifers;
- develop a 3D overburden geological model;
- develop an interpretation of depositional environments and geological history;
- identify data gaps;
- characterize all reconciled aquifers using the B.C. aquifer classification system; and
- prepare a detailed report and provide all geological models, mapping and sections in Graphical Information System (ArcGIS) and Computer Aided Design (AutoCAD) compatible formats to the B.C. ENV specifications.

2. METHODS

2.1 Field Reconnaissance

A reconnaissance of the study area was completed with well-known geologists and hydrogeologists with regional expertise including: Dr. Bob Fulton, Geological Survey of Canada (retired); Dr. Craig Nichol with the University of B.C. (UBC) Okanagan; and Mr. Skye Thomson and Mr. David Thomson, Regional Hydrogeologists with the B.C. Ministry of Forests, Lands, Natural Resource Operations, and Rural Development (FLNRO). The objective of the reconnaissance was to visit select locations within the study area that offered reasonable viewpoints of the region from which to discuss geomorphologic features and related regional stratigraphic sequences. These stops provided opportunities to discuss the glacial history and depositional environments that were likely responsible for the development of these features and stratigraphy.

The locations visited included:

- Hullcar at Community Hall;
- Salmon Arm;
- Enderby, along Inch Logan Road;
- Glenemma at junction of Salmon River Road and Highway 97;
- Silver Creek along Salmon River Road; and
- Vernon on Turtle Mountain (Turtlepin Place) looking east towards Vernon.

Information provided by Dr. Fulton was invaluable regarding the interpretation the geological sequence of events in the study area and geomorphic principles, specifically the advance and retreat of ice, formation of glacial lakes, and specific landforms. Geological maps and figures from many reports by Dr. Fulton were used during discussions in the field. Most of the reconnaissance trip was video recorded and copies of the recordings have been distributed on compact disc to the attendees.

2.2 Data Sources

The primary source of data informing the development of the 3D digital aquifer models was the B.C. WELLS Database. Additional borehole data appended to this dataset include borehole logs from the B.C. ENV Okanagan Basin study (LeBreton et al., 1972) and borehole data from a deep oil exploration program near Enderby (Enderby Oils, 1955). Existing aquifer descriptions and digital outlines (Figure 2) formed the initial starting point for this assessment.

Topology and topographic data were compiled from the TRIM data provided by B.C. ENV, and the government of Canada's Geogratis geospatial data repository (geogratis.gc.ca). Previous mapping informed many of the geologic and stratigraphic interpretations in this report. Dr. Nichol (UBC Okanagan) provided GIS data representing the most recent compilation of the overburden geology of the area (Nichol et al., 2015). This work was in turn built on earlier work including paper maps and sections compiled by Fulton (1975) and Monahan (2006), and a digital geology model by Keller (2006). Seismic data and sections provided additional constraints on the digital interpretations, including: LeBreton at al. (1972); Lundberg (1971); MacAulay and Hobson (1972); Pullan et al. (1992); and Vanderburgh (1993).

Historical stratigraphic analysis and glacial history of the study area was compiled based on papers and historical reports provided by the B.C. ENV and by Dr. Craig Nichol (UBC Okanagan), including:

Dayton & Knight Ltd., 2001	Kidston, 1993	Okulitch, 2013
EBA, 1998	Le Breton et al., 1972	Paradis, 2009
Eyles and Mullins, 1997	Le Breton, 1974	Paradis et al., 2010
Eyles et al., 1990	Lesemann, 2012	Ping et al, 2011
Fulton, 1968	Lesemann and Brennand, 2009	Pullan et al., 1992
Fulton, 1969	Lesemann et al., 2013	Roberts et al., 1992
Fulton, 1972	Livingstone, 1970	Roed and Fulton, 2011
Fulton, 1989	Livingstone et al, 2013	Roed et al., 2014
Fulton, 2006	Lowdon et al., 1967	Greenough et al., 2014
Fulton and Halstead, 1972	Miller et al, 2011	Thompson and Unterschultz, 2004
Fulton and Smith, 1978	Monahan, 2006	Thomson, 2010
Fulton at al., 1992	Mullins et al., 1990	Tribe, 2005
Golder, 2003	Nasmith, 1962	Vanderburgh and Roberts, 1996

Detailed references are provided at the end of this report (Section 7).

2.3 Analysis and Interpretation

Development of 3D geological models, including aquifer models, has traditionally been undertaken using an explicit analysis approach. This approach generally follows the following sequence of steps:

1. Define lithologic intervals in borehole (e.g., sand, clay, bedrock).
2. Define approximate limits of hydrostratigraphic units based on borehole locations and the lithology analysis.
3. Project key representative boreholes, topography and geophysical data to a series of cross sections covering the inferred footprint area of each unit.
4. Draw interpreted contacts in section view and project those sections to 3D.
5. Create upper and lower bounding surfaces for each unit based on the sectional interpretations.

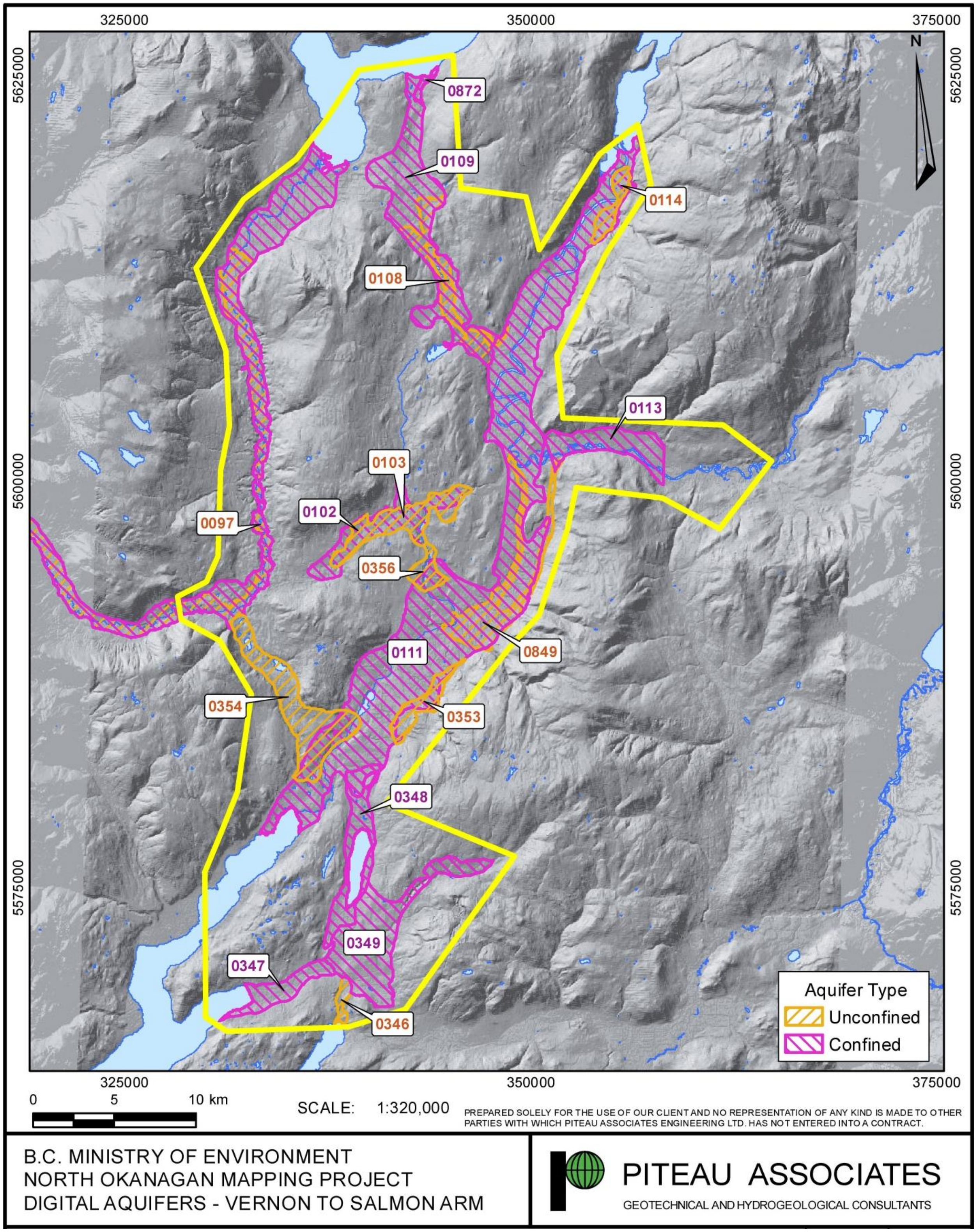

Figure 2: B.C. ENV aquifer boundaries preceding development of the 3D geologic models.

An explicit geologic modelling approach means that the final interpretation of lithologic information forces the interpreted 3D surfaces through the interpreted section-derived contacts, and through additional key contact points from the boreholes. This approach can be labour intensive, particularly if the modeller needs to iterate back and forth between section, plan and 3D view to construct the surfaces. This fixes the final model to early interpreted sectional contacts and interpreted lithology from a limited number of boreholes. Uncertainty is inherent in any geologic model. This uncertainty derives in part from the diversity found in the qualitative geologic descriptions present in borehole records, as well as the heterogeneous nature of the materials being described.

Borehole records are often constructed from fragmented cuttings and analyzed out of context of the in situ formation. As such, the ability to update an explicit model with new data, or develop multiple probable geometries to fit a dataset tends to be severely limited. These models also tend to be strongly biased by the sectional interpretations which inherently require boreholes to be projected from some distance off-section.

With the development of implicit geologic modelling platforms, like Leapfrog™, the modeller has the ability to include all data available to them, while providing the ability to quickly develop multiple realizations of 3D geology based on the same dataset. This enables the user to test multiple geologic hypotheses to fit a dataset while improving the accuracy of the model. The platform available in Leapfrog™ uses input data (topography, borehole lithology, externally derived lines and surfaces), and a variety of algorithms based on the user's conceptual inputs (stratigraphic order, erosion versus conformable contacts) to develop probabilistic 3D representations of surfaces (and from that, volumes). In simplistic terms, the user can provide "suggestions" of contacts, bedding orientations and relationships, but the model is not obliged to honour them. Leapfrog™ uses a radial-basis function that incorporates proximity to all data inputs and derivatives of those inputs to decide on contact geometries. Implicit modelling has its own unique set of limitations. For example, models cannot be forced to explicitly recognize specific data points, and too much or too little data can make it difficult to achieve a desired conceptual model. Leapfrog™ viewer files for all models generated as part of this project are included in Appendix C.

Due to the unique limitations of both geologic modelling approaches, it was decided during model development that both methods would be utilized, depending on the input data and the desired output. The explicit method was utilized to develop the bedrock-overburden interface surface in ArcGIS (Figure 3) using the borehole data, limit of overburden based on airphoto analysis, and cross-sectional projection of bedrock slopes below the overburden cover. The implicit method was used to develop most of the 3D aquifer volumes and their contact surfaces. Cross sections were not developed for the aquifer volumes, as had been anticipated in the proposal leading up to this report, because Leapfrog™ allows the user to "slice" vertical visualizations through the model on the fly, to aid interpretation of vertical stratigraphic relationships. This eliminated significant time and effort required to build detailed interpretive sections, as would have been normal for explicit analysis. The borehole geology was distilled to a simple set of groupings: aquifer material (sand, gravel and coarser material), non-aquifer material (silty sand and finer material) and bedrock. By fixing the lithology of each interval, the aquifer assigned to an interval could be continuously changed to explore different conceptual models of stratigraphy. For example, an interval which is confined in one borehole might correlate with a neighbouring unconfined interval, or it may be a separate aquifer depending on the interpreted orientation of strata, or geometry of an erosional surface. Modifications to aquifer assignment and addition of inferred contact points in areas without data were made iteratively until a favoured model was achieved.

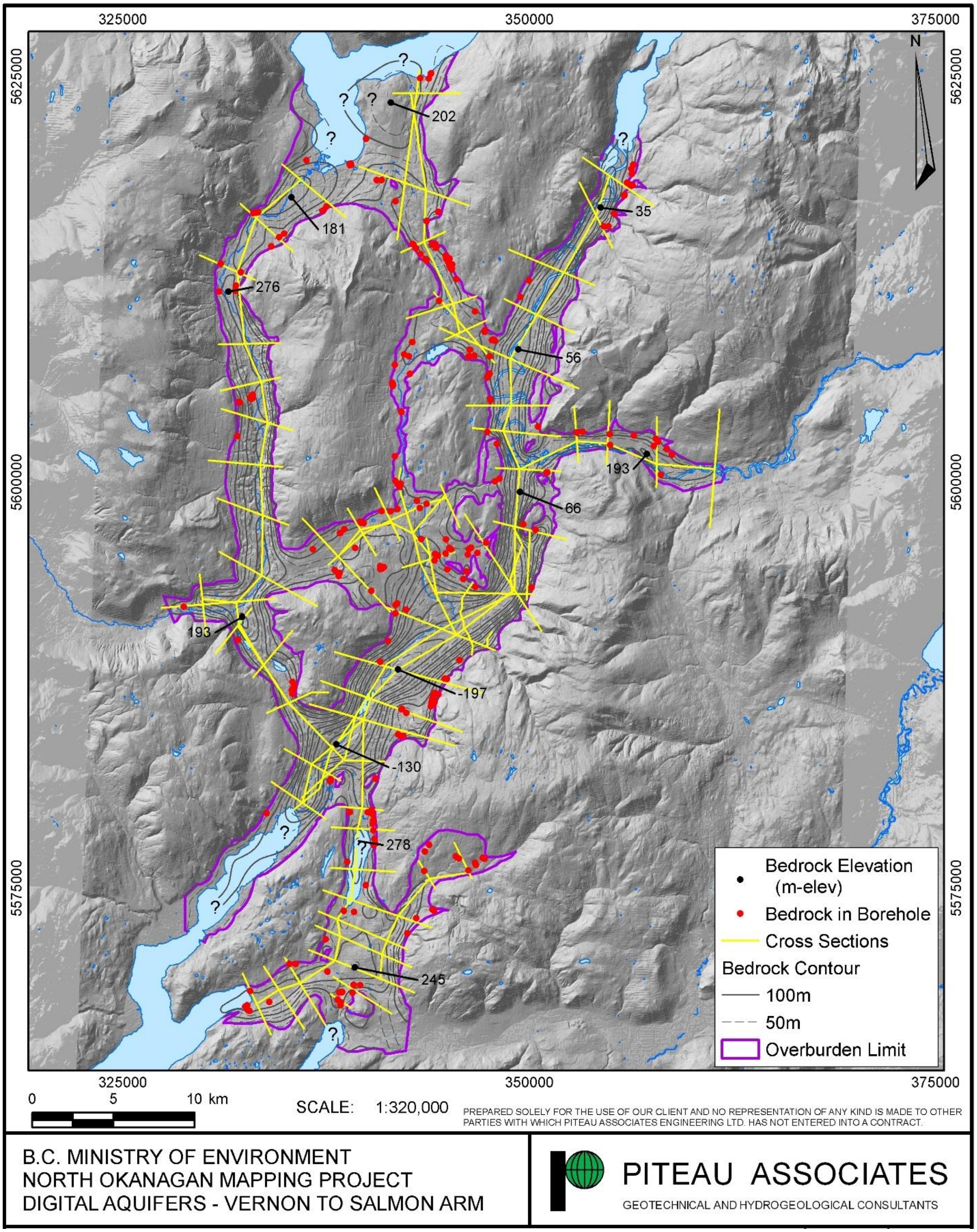

Figure 3: Bedrock surface contours, wells with bedrock intercepts, topographic low points (labeled) and cross-sections used to interpret bedrock surface.

3. OVERVIEW OF GEOLOGY

The geology of the north Okanagan has been studied in considerable detail. The most recent and comprehensive reports on bedrock geology in the study area are Thompson and Unterschultz (2004) and Okulitch, (2013). Nichol et al. (2015) provides a good review of the glacial history and overburden sequences, which is an extension of Nasmith (1962) and several papers by Fulton (1972, 1975, 1978, 2006).

3.1 Tectonic Setting and Bedrock Geology

Vernon straddles the boundary between two major tectonic terranes that make up central B.C., including Quesnellia to the south, and Kootenay to the north. Quesnellia comprises a mix of island arc rocks (volcanic, sedimentary and intrusive) of Mesozoic age accreted to the older Kootenay Terrane. The Kootenay Terrane includes Precambrian to Mesozoic age arc rocks. Local formations can include: Upper Triassic Slocan Group sediments and metasediments from argillite to sandstone, Paleoproterozoic schists in the eastern valley highlands to Mesoproterozoic schists in the south, Devonian sediments and metasediments of the Silver Creek formation and Chase formation southeast of Armstrong, Mesozoic Nicola Group sediments and volcanic rocks across the southern region of the area, between Armstrong and Vernon. Eocene-age Kamloops group volcanic rocks unconformably overlie these older assemblages north of Enderby in the Okanagan Valley and southwest of Salmon Arm in the Lower Salmon River Valley. Much of the sediment composing the local overburden that fills the valley bottoms can be inferred to derive from exposure of these terranes to erosion from mass wasting and glacial erosion. These sediments may then have been transported or reworked by glacial movement and streamflow during interglacial periods.

The Okanagan Valley is the result of a broad, north-south trending tectonic lineament (Okanagan Valley fault) of roughly 300 km length, which separates the Okanagan Plateau to the east from areas of generally lower elevation, but greater relief, to the west. An unnamed fault of similar orientation and origins is inferred to have formed the Lower Salmon River Valley. The geology of the region suggests that the major accretionary structures lie below secondary valley orientations. The major valley orientations likely owe their existence to post-accretion tectonic processes (e.g. Cordilleran Orogeny) that formed the interior plateau. Depressions along these faults would have been deepened by glacial and interglacial erosion processes, and continued tectonic movements. Earlier accretionary structures may have been reactivated, but did not impose a significant control on the overall direction of glacial ice movement.

Regional scale structures, like the Okanagan Valley fault and the valleys they form, tend to be long-lived in geological timescales. The modern topographic profile of the study area therefore likely remains little changed since the Eocene and possibly earlier (Tribe, 2005). However, the direction of ice, stream and groundwater movement appears to have changed numerous times within the established valleys, depending on the history and character of ice blockage, loading and postglacial rebound. Due to ice blockages during glacial retreat, the primary flow direction for meltwater and associated outwash sediment deposition changed several times.

3.2 Overburden Sequences and Glacial History

The most significant papers on the geological history for the area include Fulton (1975) (GSC memoir 380), Nasmith (1962) and Nichol et al. (2015). Collectively, these reports recount a succession of glacial events during the Pleistocene Epoch, including the advance and retreat of ice, down-melting and the formation of lakes.

Nichol et al. (2015) define 11 stratigraphic units in the north Okanagan, based on multiple glacial episodes during the Pre-Wisconsin, Early/Middle Wisconsin, Olympia (non-glacial), and Wisconsin/Fraser periods. The numbers of these episodes that are preserved in identifiable units in the area is unclear.

Nichol et al. (2015) suggested that the lowermost stratigraphy filling the valley bottom is glacial and interglacial sediments of uncertain Pleistocene age (pre-Wisconsin). Using their naming convention, the deepest units, I, II and III are defined as pre- or early Wisconsin in age, primarily based on the presence of organic material. Unit IV is a relatively thick unit of lacustrine silts deposited during the non-glacial Olympia (Middle Wisconsin) period. Units I through IV (and possibly V) are relatively continuous in the study area, within the main Okanagan Valley, extending from Vernon to Mara Lake. These units may not have been disturbed by ice advance/retreat during the Fraser glaciation.

Units V through XI are from the Fraser glaciation (middle to late Wisconsin) periods and therefore younger, although they may be partly composed of reworked material from earlier periods. All the aquifers in the area mapped by the B.C. ENV are within these shallow units.

In general, the stratigraphy from bottom (oldest) to top (youngest) is as follows:

- pre-Wisconsin (Units I, II);
- unconformable sands and gravel of early Wisconsin age or older than 65,000 years (Unit III);
- unconformable mid Wisconsin interglacial (alluvial & lacustrine) material, abundant organic material (grass, trees, etc.), also known as the Bessette sediments that are from 23,000 to 65,000 years old (Unit IV and Unit V);
- unconformable reworked alluvium and outwash deposits of pre- to early Fraser Glaciation age, or older than 23,000 years (Unit VI and VII, and possibly top of unit V);
- glacial kame, till and glaciolacustrine deposits along valley margins (Units VI and VII);
- Fraser and post Fraser glaciolacustrine sediments, inter-fingered with recessional glacio-deltaic sediments (Unit VII to XI); and
- late Holocene fluvial down-cutting with channel fill from current alluvial environments (unit XI).

Table 1 shows stratigraphic units with comparison against earlier studies (after Nichol et al. 2015).

The extent and thickness of hydrostratigraphic units is a function of the orientation and persistence of ice in the base of the valleys, deposition resulting from sediment-laden meltwater flow into the valleys and along the edges of the ice, and the extent of large glacial lakes.

During the advance of glaciers during the Fraser period, the uppermost portion of Unit V, the Bessette sediments from the Olympia non-glacial period, was eroded and compacted. Sediment reworking and deposition at the base of the valley-filling glaciers created a discontinuous basal till layer overlying the Bessette sediments. This discontinuity is visible in most boreholes which penetrate to sufficient depth. In many cases deposition of till during glaciation forms a distinct confining layer between upper and lower aquifers in the region. However, at some locations this intervening till is poorly developed, or has been eroded away. Consequently, there may be localized hydraulic communication between upper and lower aquifers through windows in the confining till. When this layer is completely absent (e.g. portions of the Hullcar and O'Keefe valleys) upper and lower stratigraphic units may be in full contact and thus act as a single hydrostratigraphic unit (i.e. aquifer). This hydraulic contact is never complete across the entire footprint of the aquifer, and thus separate aquifer units are retained in these cases.

Table 1: Correlation of aquifers, previous aquifer subdivisions, and revised subdivisions.

LEAPFROG Unit	Unit Subdivision	Previous B.C. ENV Aquifer #	Previous Name	Location	Updated B.C. ENV Aquifer #	Updated Name
AC0		113	Ashton Creek	Ashton Creek	**1149**	Ashton Creek Unconfined
AC1		113	Ashton Creek	Ashton Creek	**113**	Ashton Creek Basal
BX1		349	BX Creek	Northeast of Vernon along BX Creek	**349**	BX Creek
HC0		103	Hullcar Unconfined	Parkinson Lake	**103**	Hullcar Unconfined
HC1		102	Hullcar Confined	Hullcar	**102**	Hullcar Basal
		356	Deep Creek / Sleepy Hollow	Mouth of Deep Creek	**356**	Deep Creek
SR0		97	Lower Salmon River Unconf.	Falkland to southwest of Salmon Arm	**97**	Salmon River Unconfined
SR1		98	Lower Salmon River Confined	Lower Salmon River Valley	**98**	Salmon River Confined
OK0		354	O'Keefe	O'Keefe Valley and Grandview Flats	**354**	O`Keefe Unconfined
OK1		354	O'Keefe	O'Keefe Valley and Grandview Flats	**1150**	O`Keefe Basal
OR0	**OR0-A**	111	Spallumcheen	Lower Shuswap River Valley	**111**	Okanagan Valley Unconfined
		849	Fortune Creek	NE of Armstrong		
	OR0-B	348	Swan Lake	Just north of Vernon to north of Swan Lake	**1151**	Swan Lake Unconfined
	OR0-C	349	BX Creek	Northeast of Vernon along BX Creek	**1152**	Vernon Unconfined
	OR0-D	346	South Vernon	Kalamalka Lake to Vernon	**346**	South Vernon Unconfined
		347	Okanagan Lake	Vernon to Okanagan Lake		
	OR0-E	353	Eagle Rock	SE of Armstrong	**353**	Eagle Rock Unconfined
	OR0-F	114	Mara	South of Mara Lake	**114**	Mara Lake Unconfined
OR1	**OR1-A**	111	Spallumcheen	Lower Shuswap River Valley	**1153**	Okanagan Valley Confined
	OR1-B	348	Swan Lake	Just north of Vernon to north of Swan Lake	**348**	Swan Lake Confined
	OR1-C	349	BX Creek	Northeast of Vernon along BX Creek	**1154**	Vernon Confined
	OR1-D	347	Okanagan Lake	Vernon to Okanagan Lake	**347**	South Vernon Confined
OR2		111	Spallumcheen	Lower Shuswap River Valley	**1155**	Deep Okanagan Valley
OR3		111	Spallumcheen	Lower Shuswap River Valley	**1156**	Basal Okanagan Valley
TH0	**TH0-A**	108	Tuhok Unconfined	4 kilometres southeast of Salmon Arm	**108**	Tuhok Unconfined
	TH0-B	872	Canoe Creek	Canoe Creek, at Shuswap Lake	**872**	Canoe Creek
TH1		109	Tuhok Confined	Highway 97B	**109**	Tuhok Confined
HC0	**aHC**			Slopes of Hullcar Valley, near Deep Creek	**1157**	Hullcar Perched

Note: Aquifer numbers highlighted in red are new aquifer subdivisions presented in this report, those in black are inherited from existing aquifer descriptions. The 'Leapfrog Unit' designation refers to a vertical (hydrostratigraphic) aquifer subdivision where: Unit 0 is an unconfined aquifer, Unit 1 is an upper confined aquifer, Unit 2 is a deep confined aquifer, and Unit 3 is basal confined aquifer. This unit is also subdivided geographical by a location code (assemblage) where: OR is the Okanagan Valley, SR is the Lower Salmon River Valley, OK is the O'Keefe Valley, HC is the Hullcar Valley, TH is the Tuhok Valley, AC is Ashton Creek (Shuswap River Valley), and BX is the Upper BX Creek Valley.

Table 2: Correlation of proposed aquifer units, stratigraphic unit, period and previous aquifer subdivisions.

AQUIFER	**Primary Valley**		**Secondary Valley**			**Tertiary Valley**		Unit Nichol et al. (2014)	Period	Previous B.C. ENV Aquifer Numbers
	OR	**SR**	**OK**	**HC**	**TH**	**AC**	**BX**			
	Lacustrine, bog, unsaturated alluvium and colluvium							XI	Holocene	
Unit 0	Unconfined Aquifer					Alluvial Fan		Unit VII, VIII, IX, X and XI	Late Glacial (Including reworked preglacial) to Holocene	97, 103, 108, 111, 113, 114, 347, 348, 349, 353, 354
	Mixed kame, till, ice-contact glaciolacustrine deposits							Unit VI and VII	SYN to Post Glacial	
Unit 1	Upper Confined Aquifer					Basal Fan		Unit V and VII	Pre-Glacial, Reworked Pre-Glacial, Syn-Glacial	98, 102, 109, 111, 113, 114, 146, 346, 347, 348, 349, 353, 354, 356, 872
	Non-glacial alluvial plain, lacustrine, bog and marsh							IV	OLYMPIA NON-GLACIAL	
Unit 2	Deep Confined Aquifer							IV	OLYMPIA NON-GLACIAL	111
	Non-glacial alluvial plain, lacustrine, bog and marsh							IV	OLYMPIA NON-GLACIAL	
Unit 3	Basal Aquifer	(Unit 1?)						Unit II/III	POST-GLACIAL	109, 111, 349, 354, (102, 356)
	Mixed fine-grained basal sediments, including till							Unit I/II	OKANAGAN CENTER GLACIATION	

4. RECONCILIATION OF AQUIFERS

The objective of this assessment is to provide the technical rationale behind recommended changes to the list of current aquifers in the study area, as presented in Table 1. As illustrated in Table 2, the results indicate that several of the current aquifers are likely contiguous and of similar hydrostratigraphy. Table 1 introduces the naming convention used to delineate the revised aquifers presented in this assessment.

For example, the Hullcar Valley contains aquifers HC0 (unconfined) and HC1 (confined). These units roughly correspond to stratigraphic ages presented in Nichol et al. (2015). Some uncertainty exists where documentation of stratigraphy is incomplete or absent. For example, HC1 is the lowermost unit in the Hullcar Valley and could correlate in time with any or all of OR1, OR2 or OR3 in the adjacent valley. Summary maps of the revised aquifer extents are provided in Figures 4, 5 and 6, according to the aquifer unit.

Retaining purely hydrostratigraphic subdivisions for this assessment may represent challenges for managing aquifer resources in the region. For example, the current unconfined Spallumcheen, Swan Lake, Vernon, South Vernon, Eagle Rock and Mara Lake Aquifers are interpreted to be a single hydrostratigraphic unit of similar age and composition, and all compose part of the overburden filling the Okanagan Valley. While technically a single hydrogeological aquifer (hydrostratigraphic unit), the locations, usage and inherent risks warrant retaining previous subdivisions for management purposes, while still recognizing regional hydrogeological continuity.

The primary changes to the assemblage of aquifers in the study area are as follows:

- Division of the Ashton Creek Aquifer (113) into an unconfined (1149) and confined (113) aquifer.
- Splitting the BX Creek Aquifer (349) into one aquifer in the upper reach of BX Creek (349), and inclusion of the remainder as the Vernon Unconfined and Confined Aquifers as subdivisions of the regional Okanagan Valley Aquifer (1152).
- Division of the O'Keefe Aquifer (354) into an unconfined (354) and confined (1150) aquifer
- Recognition that the Spallumcheen (111), Okanagan Lake (347), Fortune Creek (849), Swan Lake (348), Lower BX Creek (349), South Vernon (346), Eagle Rock (353) and Mara Lake (114) Unconfined Aquifers are hydrostratigraphically a single aquifer, however separate aquifer numbers are retained for management purposes.
- Recognition that the Spallumcheen (111), Okanagan Lake (347), Swan Lake (348), and Lower BX Creek (349) Confined Aquifers are hydrostratigraphically a single aquifer, however separate aquifer numbers are retained for management purposes.
- Definition of discrete Deep Okanagan Valley (1155) and Basal Okanagan Valley (1156) Aquifers.

The boundaries of following aquifers remain unchanged:

- Hullcar Unconfined Aquifer (103)
- Hullcar Confined Aquifer (102)
- Deep Creek Unconfined Aquifer (356)
- Lower Salmon River Unconfined Aquifer (97)
- Lower Salmon River Confined Aquifer (98)
- Tuhok Unconfined Aquifer (108)
- Tuhok Confined Aquifer (109)
- Canoe Creek Confined Aquifer (872)

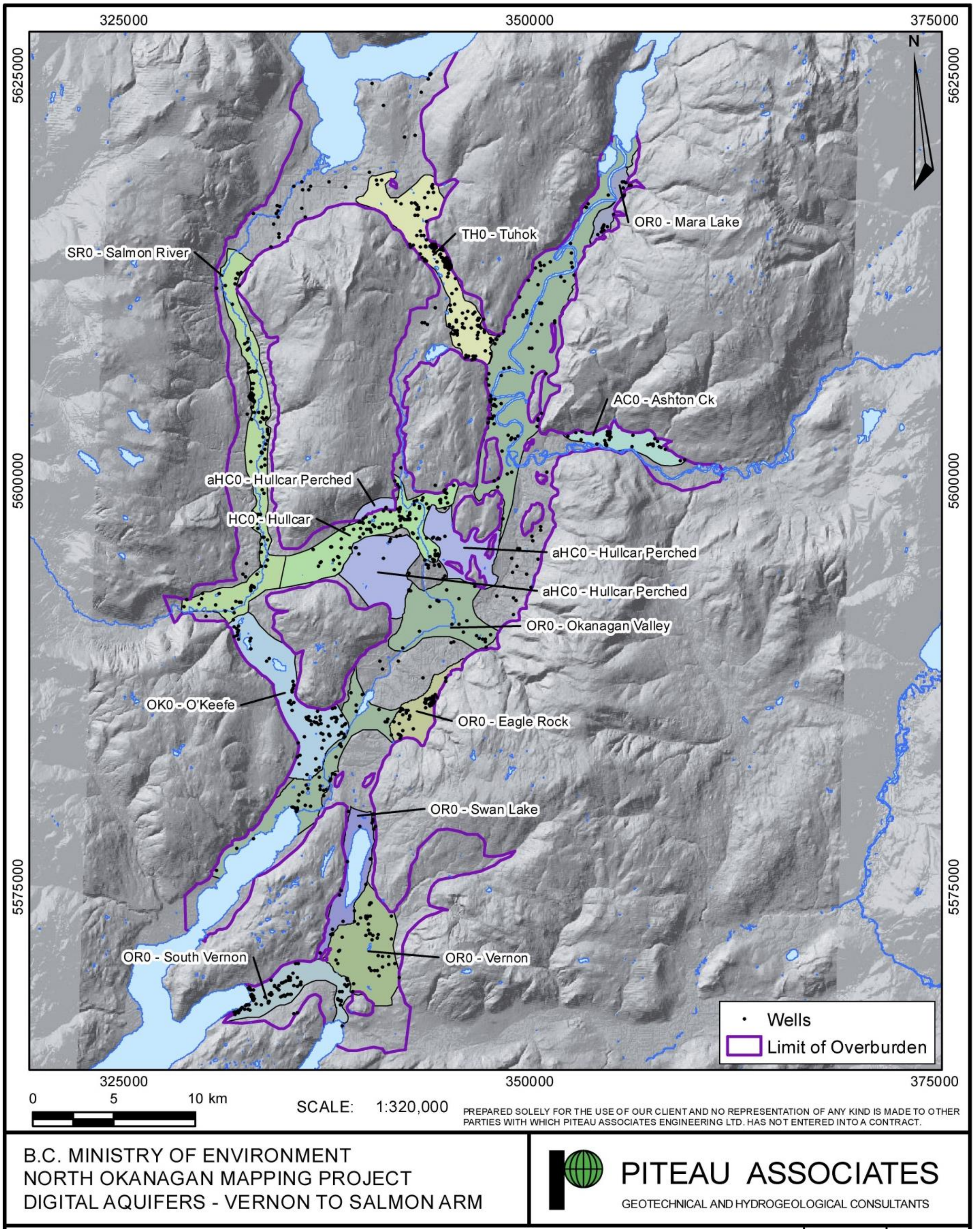

Figure 4: Aquifer mapping, extent of unconfined aquifers.

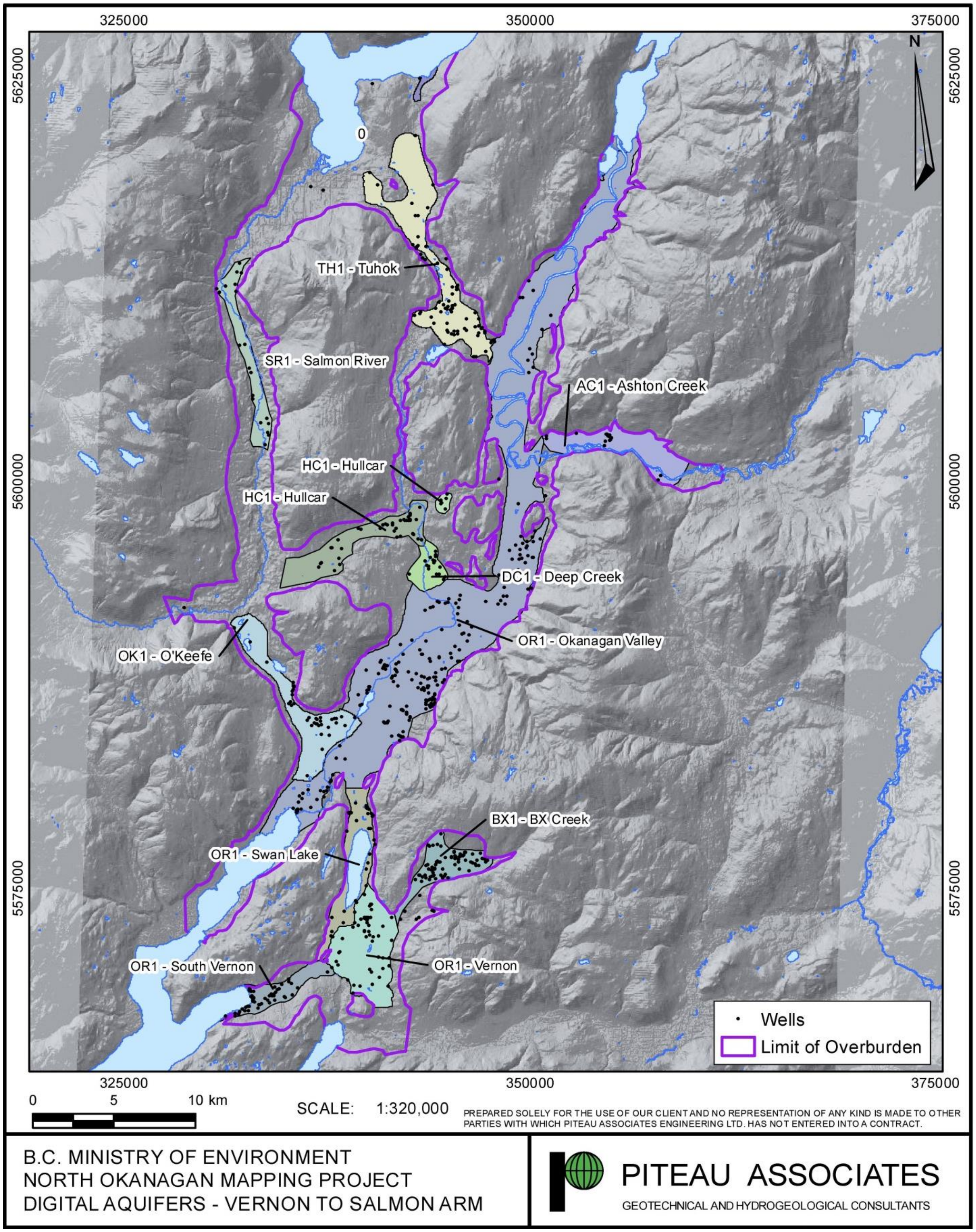

Figure 5: Aquifer mapping, extent of upper confined aquifers.

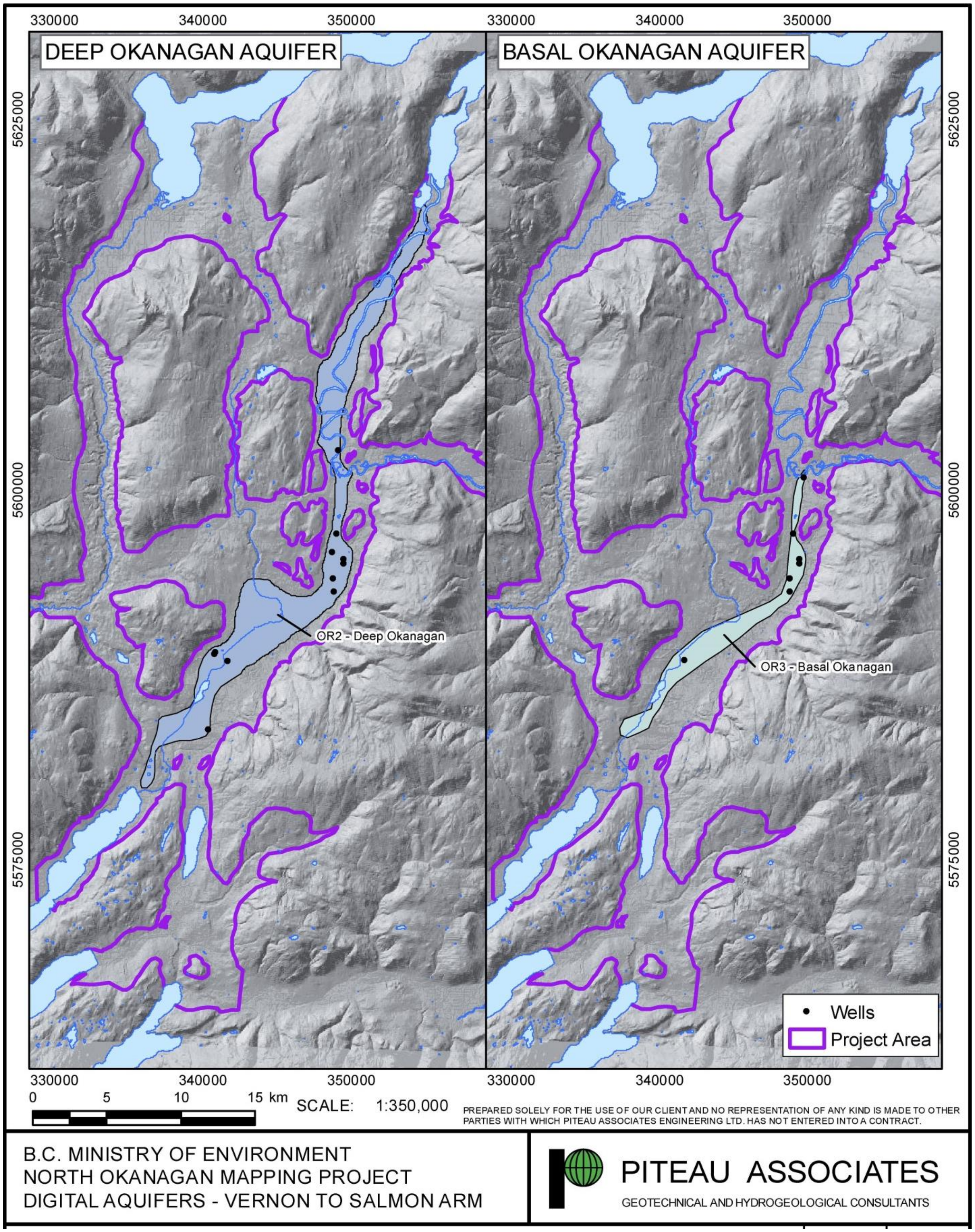

Figure 6: Aquifer mapping, extent of deep and basal aquifers.

One new aquifer area (1157) is recommended that defines a region in which smaller discontinuous aquifers are present and are utilized for groundwater extraction. This new area includes shallow aquifers below hill slopes surrounding the intersection of Deep Creek and the Hullcar Valley, and is defined as the Hullcar Perched Aquifer area.

Detailed descriptions of the revised aquifers are presented below, according to geographic assemblage. Each individual aquifer is documented in detail in Appendix A. Lateral hydraulic connections between the different aquifer valley areas are highlighted in Table 3. Images of the 3D aquifer block model are presented in Figures 7 to 14 in the following sections.

Table 3: Contact relationships between aquifers.

	AC	**BX**	**HC**	**OK**	**OR**	**SR**	**TH**
AC							
BX	n/c						
HC	n/c	n/c					
OK	n/c	n/c	n/c				
OR	no correlation	no spatial correlation; genetic link	vertical contact; interfingered fan?	vertical contact; interfingered fan?			
SR	n/c	n/c	GW divide; continuous alluvium	GW divide; continuous alluvium	n/c		
TH	n/c	n/c	n/c	n/c	Significant elevation difference	Significant elevation difference	

n/c = no connection
AC = Ashton Creek
BX = BX Creek
HC = Hullcar
OK = O'Keefe
OR = Okanagan River Valley
SR = Salmon River
TH = Tuhok

4.1 Okanagan Valley

The Okanagan Valley hosts a series of regionally semi-continuous aquifers (Figure 7 and Figure 8) including an unconfined shallow aquifer (OR0) and at least three deeper confined aquifers (OR1 to OR3). Most accessible groundwater in Okanagan Valley is produced from the pre- to late glacial sediments of aquifer OR1 or late to post glacial sediments of aquifer OR0 that lie between 20-100 metres below ground surface (m-bgs). There is generally good vertical separation of aquifers OR0 through OR3 by intervening fine-grained confining units. Laterally, aquifer sediments appear to be relatively continuous; however, recognizing the variations in usage and location, earlier subdivisions are maintained for management purposes (Figure 4 and Figure 5). Geologic relationships and facies are complex. While the sediments which compose the aquifer are extensive and represent relatively continuous hydrostratigraphy, they likely do not represent a single coherent stratigraphic unit. Borehole logs suggest that aquifer OR1 includes in-situ preglacial sediments, glacial reworked preglacial sediments as well as early pro-glacial sediments associated with unit V and VII. The unconfined aquifer OR0 may contain late glacial (including reworked preglacial) kame and alluvial sediments as well as post-glacial Holocene alluvial deposits. It is apparent from modelling that lithologic subdivisions likely do not reflect stratigraphic subdivisions. Resolving hydrostratigraphic boundaries from borehole logs does not necessarily inform resolution of stratigraphic boundaries.

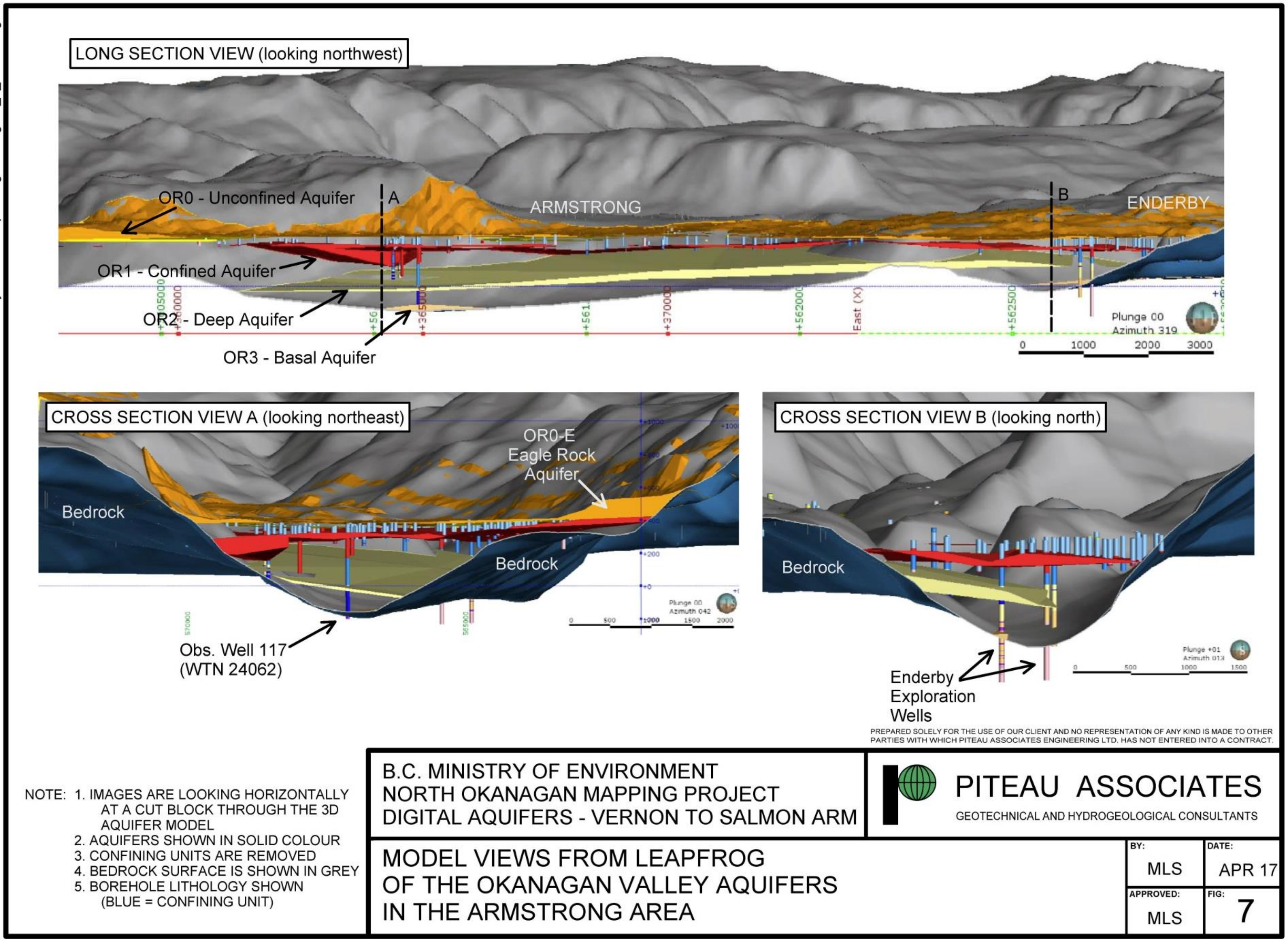

Figure 7: Model views from Leapfrog of the Okanagan Valley Aquifer in the Armstrong area.

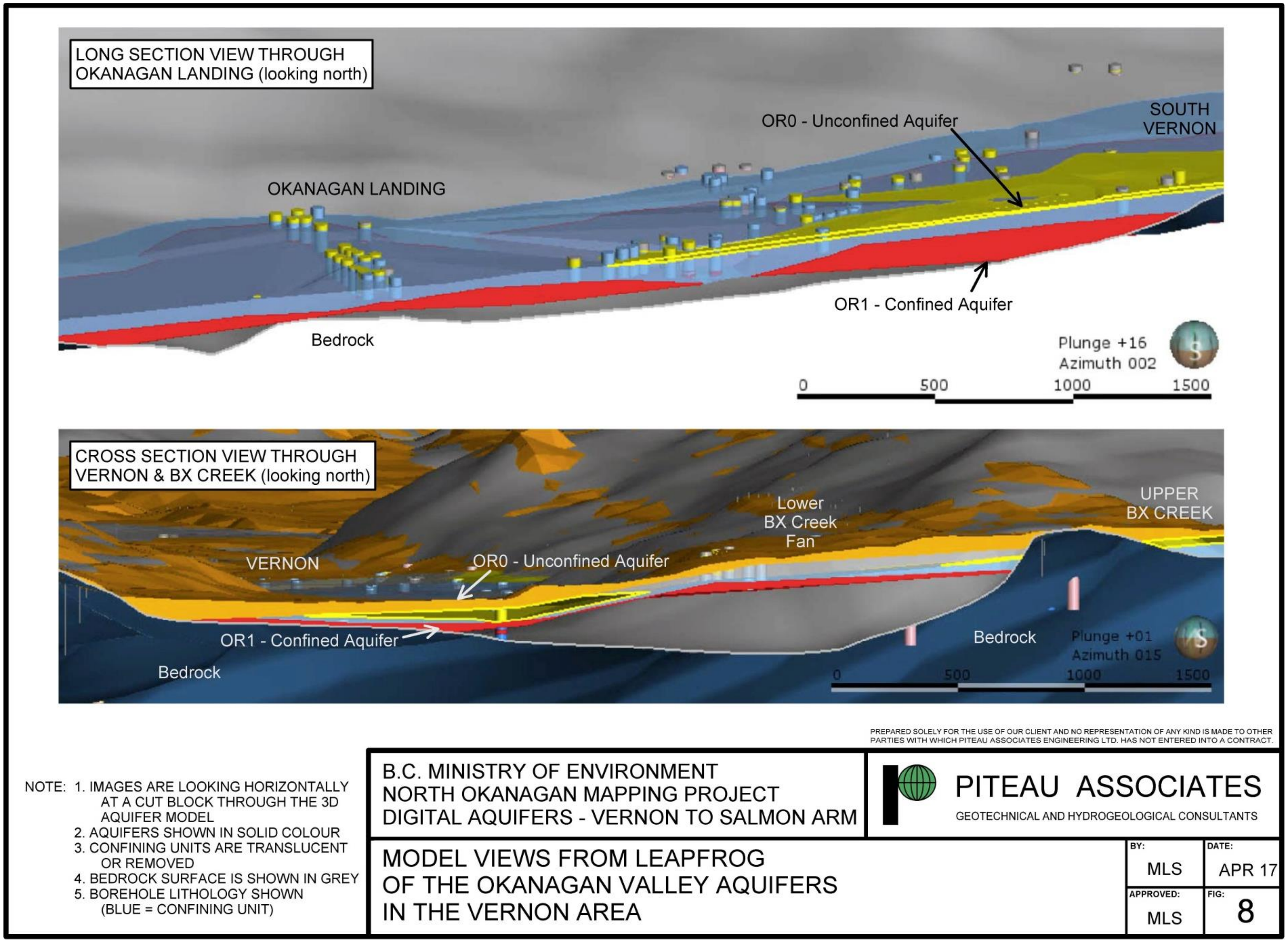

Figure 8: Model views from Leapfrog of the Okanagan Valley Aquifer in the Vernon area.

Aquifers in the valley are predominantly confined, relatively continuous, have a low topographic gradient and are lower in elevation than the thalweg of the valley. In central portions of the valley, the confined aquifers tend to be composed of lower conductivity sand to fine sand, while the upper unconfined unit may be coarser-grained sand to sand and gravel. This central zone is flanked by local coarse-grained alluvial fans and colluvium deposited at the outlet of secondary and tertiary valleys. Some of these alluvial fans are the most productive aquifers in the study area. Aquifer recharge is from vertical infiltration (precipitation and irrigation), and lateral recharge from flanking alluvial fans, colluvial cover, basal sediments at the bedrock contact and highly fractured or faulted bedrock (mountain-block recharge, or MBR). A significant amount of water may be received from secondary valley systems, which provide substantial catchments for groundwater. Aquifers may recharge from, or discharge to valley lakes and rivers, depending on overall gradient and local topographic variability.

Underlying deep aquifers (Figure 6) may see a limited amount of recharge. There are no obvious discharge points, and few significant pumping wells installed in these aquifers, and thus water likely resides in storage for relatively long periods in comparison to upper aquifers. Large scale topographic trends generally drive the slow movement of groundwater through these aquifers, with stresses such as aquifer pumping and artesian conditions in underlying bedrock from mountain block recharge generating local higher flow gradients. Utilization of these aquifers appears limited. Well records indicate that the communities of Enderby and Armstrong have high yielding wells completed in the deeper aquifers, but are not currently being utilized. The deep aquifers below the Okanagan Valley are generally of lower hydraulic conductivity, but high volume, and represent a large reservoir of stored groundwater.

Portions of OR0 including Eagle Rock (OR0-E), Mara Lake (OR0-F) and Swan Lake (OR0-B) are dominantly gravel and sand aquifers. These aquifers are interpreted to be alluvial fans including reworked pre- and post-glacial derived sediment. The South Vernon (OR0-D) and Okanagan Valley (OR0-A) segments of the aquifer are organic-bearing sand and gravel while the Vernon segment is fine to coarse-grained sand, and can be cemented or compacted reflecting possible late glacial compaction.

Minor accumulations of clay, sandy clay and till (kame deposits) are noted to overlap margins of the Okanagan Valley segment, and most of the Swan Lake segment of the aquifer. The Mara and Eagle Rock segments both contain a discontinuous clay layer which may be equivalent to the confining unit separating OR0 and OR1 in the Okanagan Valley and other segments the aquifer. The extent of this unit is inferred to be too limited to generate significant confinement of the lower aquifer, and thus do not warrant vertically subdividing these segments of the aquifer.

The aquifer between Okanagan Lake and Mara Lake is the largest continuous segment of aquifer OR0, covering about 170 square km. This segment has the lowest density of wells (0.3/square km) in the study area. This average density does not reflect local densities of wells present between Armstrong and Enderby, and other areas. In contrast, the highest well densities in the study area are in the Eagle Rock and Mara segments of the aquifer with 10 and 5 wells/square km, respectively. The footprints of these aquifer segments are relatively small, so utilization is local, but very high.

Within the OR0 aquifer, the highest average well yields are recorded in the Eagle Rock and South Vernon segments. High average yields are consistent with the highest recorded maximum individual yields. The highest yield in the study area is 51.7 liters per second (lps) recorded at Eagle Rock. Mean yields are recorded in the Spallumcheen segment, while the lowest average yields are from Vernon, Mara Lake and Swan Lake segments. The Swan Lake sediment appears to be particularly limited with only thin discontinuous lenses of sand and gravel at surface in shallow dug wells, or under shallow clay cover (<10m) in borehole. Many of the flanking alluvial fans, including Eagle Rock and Mara Lake, are interpreted to be a significant source of recharge to aquifer segments farther away from the valley walls (Spallumcheen), resulting in artesian conditions in the upper confined aquifer.

The upper confined aquifer (OR1) comprises gravel to sand and gravel in the South Vernon, Vernon and Swan Lake segments, and fine to medium sand in the Okanagan Valley segment. Swan Lake, Okanagan Valley and South Vernon OR1 aquifers are all in the upper 50% of average well yields for the aquifers studied, and overall tend to be higher than their unconfined counterparts. The exception is the Vernon segment of OR1 which has a low average yield like its unconfined counterpart in aquifer OR0.

The composition of the confining unit separating aquifer OR0 from OR1 is variable. In the Okanagan Valley, South Vernon and Swan Lake segments, the confining unit tends to be dominantly blue-grey clay, silty clay to sandy silt with organics including wood, grass and shells. Till is also noted from borehole logs. The confining unit below Vernon includes gravelly clay, till and minor silt.

A limited number of boreholes penetrate the deep stratigraphy of the Okanagan Valley (Figure 7). The composition of aquifers OR2 and OR3 inferred from these boreholes is sand to silty sand, which is compacted or cemented in places. A confining unit separating these two aquifers is composed of silt, with minor clay and varying amounts of sand. Organics and plant debris, including carbonaceous wood, are common. The limited number of well completions tend to be higher in yield, although may not be indicative of aquifer capacity. The high yield is likely a function of higher available head and greater total aquifer thickness as the aquifer is relatively fine grained compared to other aquifers in the region. Average water depths for the Okanagan Valley Aquifers range from 6-15 m-bgs, although may be greater than 25 m-bgs in the Vernon Unconfined Aquifer. The average water depth in the unconfined aquifer is 11.5 m-bgs and in the confined aquifer is 12.9 m-bgs, essentially the same within reasonable error. The range of water depth is low in comparison to the range of elevation of the aquifers as there are few subsurface boundary conditions that could drive heads lower.

4.2 Lower Salmon River Valley

Aquifers in the Lower Salmon River Valley (SR0 an SR1) are of similar character to those in the larger Okanagan Valley, although the proportion and thickness of finer grained, lower energy sediments is much less given the narrower, confined nature of the valley (Figure 4, Figure 5, and Figure 9). The upper unconfined aquifer comprises fine to medium grained sand with lesser sand and gravel. The aquifer is compacted in places and can have extensive thicker accumulations of confining clay and till along its margins which are interpreted to be a mix of kame, colluvium and alluvial fan deposits. The deeper confined aquifer is made up of clean fine to medium sand, with minor gravel and boulders. Some boreholes encountered organic material. This aquifer is confined by a semi-continuous grey to blue clay to silty sand layer (e.g. below Yankee Flats, Figure 9), which can contain shells and organic material. The discontinuous nature of the confining unit, renders it difficult to differentiate this aquifer from the overlying unconfined aquifer in some boreholes. This implies that the aquifer could act in an unconfined manner in places, and may be hydraulically connected to surface waters.

Whereas, the upper confined aquifer in the Okanagan Valley is utilized most by groundwater extraction wells, groundwater production in the Lower Salmon River Valley is predominantly from the unconfined aquifer. Wells in the unconfined aquifer are completed mainly 10-30 m-bgs, while wells in the lower confined aquifer tend to be 20-40 m-bgs. Average well yields from these aquifers are about 2.5 lps, which is about mid-range for the study area. This could be a function of lower demand from the dominantly rural population and minimal industry in the valley compared to other regions, rather than a reflection of potential aquifer yields. Irrigation may rely on local hand-dug wells, close to the Salmon River, which may be under-reported. In terms of the average density of wells in the two aquifers, both are mid-range between 2-3 wells/square km.

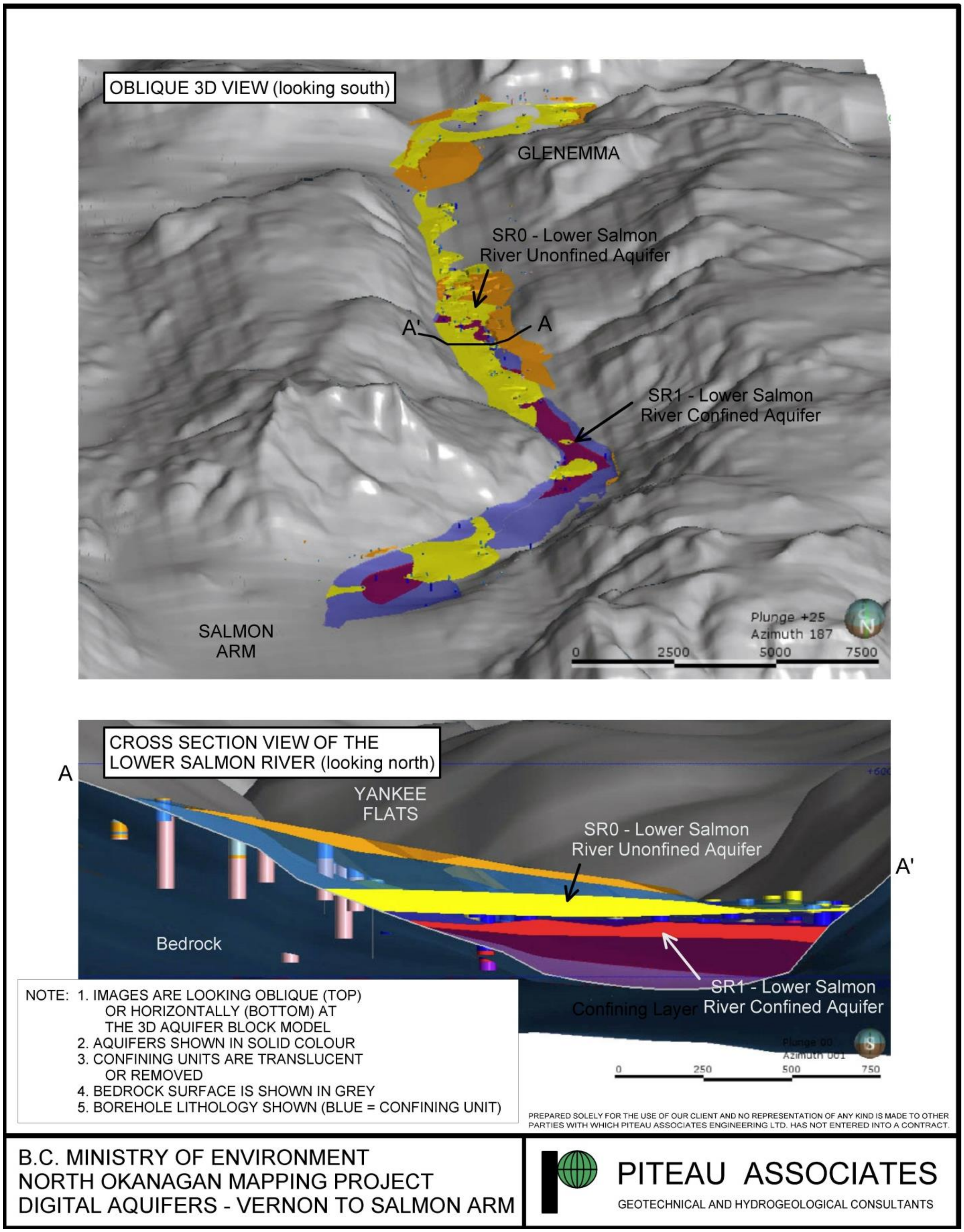

Figure 9: Model views from Leapfrog of the Lower Salmon Rivers Aquifers.

The average water level in the confined aquifer SR1 (7.6 m-bgs) is higher than that in the unconfined aquifer SR0 (12.6 m-bgs), implying the system on average has an upward hydraulic gradient. This report recognizes that the analysis of water levels was very limited during this assessment, and that actual groundwater conditions will be significantly more complex than the averages presented in Appendix A.

4.3 Hullcar Valley

The SECONDARY valleys in the study area (including the Hullcar, O'Keefe and Tuhok Valleys) have proportionally thicker and more extensive coarse-grained aquifers (coarse sand, and gravel) than the MAIN valleys, but are of similar character and geologic history. The Hullcar Valley hosts two distinct aquifers, an upper unconfined and lower semi-confined aquifer, separated by a semi-continuous to discontinuous confining unit (Figure 10). Both aquifers are primarily sand with lesser sand and gravel, and may be compact or cemented in places. The lower unit is noted to have organics in places, including wood fragments. The intervening confining unit comprises dominantly sandy to silty till, with lesser clay units. This unit is more extensive in the Hullcar Valley than the equivalent unit in the O'Keefe Valley, however windows through this unit are still present in the Hullcar Valley (Figure 10). Where present, these windows connect the upper unconfined aquifer with the lower confined aquifer.

The upper aquifer, HC0, appears stratigraphically equivalent to SR0 and OR0 as late glacial outwash formed when ice blocked both the Lower Salmon River and O'Keefe Valleys. This blockage likely forced surface water from the largely open headwaters of the Lower Salmon River Valley to enter the Hullcar Valley from the west, and flow out to the east and south into the Okanagan Valley. Compaction and the presence of Parkinson Lake, a kettle lake, attest to the late glacial origins of aquifer HC0. Where Deep Creek enters the Hullcar Valley, a portion of HC0 is overlain by till which stretches upstream into the Deep Creek Valley. This suggests that while the main Hullcar Valley was free of ice, a small tongue of ice may still have fed into the valley from higher elevations to the north in upper Deep Creek.

Aquifer HC1 overlies, and is locally overlain by till and silty sediments. The presence of organics within the unit suggests that deposition may span post Okanagan center glaciation through to pre or early Fraser glaciation and could be associated with stratigraphic units III to V. Upper portions of this deposit may have been reworked and compacted during early Fraser glaciation. Coarser grained sediments appear to be spatially linked to lower portions of the Deep Creek/ Sleepy Hollow Aquifer (aquifer 356; Figure 10). In the paleo-Deep Creek Valley, based on borehole logs, contacts between till and HC1 sediments appear steep to vertical. Hydrostratigraphic relationships and topography suggests that the former Deep Creek Valley was deeply incised prior to deposition of a thick alluvial fan associated with the downstream portion of HC1 (i.e., aquifer 356). Slightly upstream of this fan below Deep Creek, the confining unit described above appears to pinch out. Upper portions of this lower fan are likely also contiguous with HC0, and are hydraulically well-connected below the outlet of the Hullcar Valley.

In the most recent study in this area, which was commissioned by a collaborative B.C. government inter-ministry working group, and focused on water quality, Golder (2017) suggests that, while two lithologically distinct aquifer units exist within the main Hullcar Valley, they are sufficiently hydraulically connected, such that they act as one aquifer over substantial regions. Accordingly, in Golder (2017), silty sands were included within the aquifer unit.

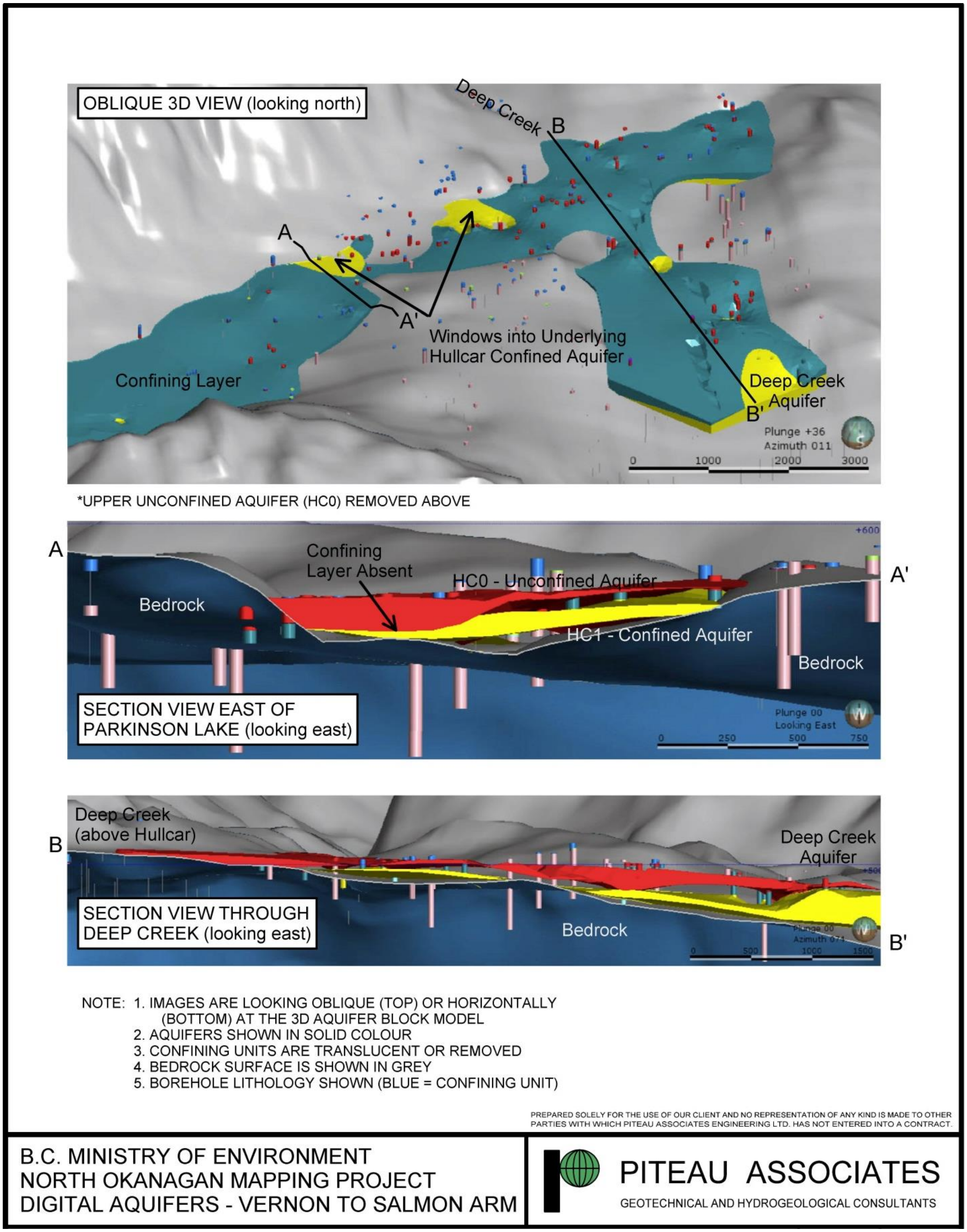

Figure 10: Model views from Leapfrog of the Hullcar Aquifers.

This study agrees with Golder's assessment that the hydrogeology of the area is complex. However, this study focuses on the larger scale hydrostratigraphy. In this study, silt-bearing soils are interpreted to be sufficiently distinct from the materials defining the aquifers, that they warrant subdivision. The silt unit appears to be relatively thick and continuous between most boreholes. In addition, the average depth to water for boreholes completed in the underlying unit is distinctly greater (26 m-bgs) than that of the upper unconfined aquifer (11 m-bgs). Golder identified downward hydraulic gradients in several areas, suggesting these reflect pumping and/or recharge. They might also be indicative of hydraulic separation of two distinct aquifers.

Additional study regarding the relative hydraulic conductivity of the various units and of the vertical and horizontal hydraulic gradients would be required to fully characterize groundwater issues associated with the Hullcar system. Accordingly, Golder (2017) recommends the development of a numerical groundwater model for the Hullcar area to better constrain the conceptual model of the Hullcar area as well as field investigations including the installation of monitoring wells to refine the stratigraphic understanding of the Hullcar Valley.

The topographic gradient along the base of Hullcar and other secondary valleys is steeper than that in the main valleys. These secondary valleys tend to be oblique to the direction of glacial movement, when ice was at its thickest. These two features are possible reasons for higher proportion of coarse-grained aquifer material versus fine-grained aquifer and non-aquifer overburden in the secondary versus the main valleys. The Hullcar, O'Keefe and Tuhok Valleys all debauch into the Okanagan Valley from substantially higher elevations. As a result, significant alluvial fans have been developed at the mouth of the first two, and to lesser extent below Tuhok.

Recharge to the secondary valley aquifers originates in intermediate catchments between the main valleys. The Hullcar Valley does not appear to be recharged from the west due to a topographic high in bedrock below the entrance to the valley from the Lower Salmon River Valley. Precipitation and irrigation provide direct recharge over the aquifer, while upland areas provide water to the aquifers via MBR, along colluvial slopes and alluvial fans. Discharge from the secondary valley aquifers can take the form of springs or artesian flow to surface, or may provide recharge to main valley aquifers along age-equivalent strata or across unconformable contacts with main valley stratigraphy. Kettle lakes are a common feature of all three secondary valleys and provide sites for groundwater discharge and evaporation during the dry season, and infiltration of precipitation during the wet season. Discharge from the Hullcar Aquifers is to the Okanagan Valley via the Deep Creek Aquifer.

Average well yields to the Hullcar Aquifers are some of the highest in the study area. The average yield for wells completed in the unconfined aquifer HC0 is 4.7 lps, while the average yield from HC1 is 7.3 lps, the highest in the study area. The high yields attest to a combination of high static water levels, higher conductivity aquifer sediments and likely higher demand (larger well completions) from the intensive agriculture present in the valley. The density of wells completed in the Hullcar Valley aquifers is moderate to high for the study area, about 3.2 wells/square km.

4.4 O'Keefe Valley

The hydrostratigraphy of the O'Keefe Valley is strongly analogous to that of the Hullcar Valley, although somewhat simplified due to its linear geometry and lack of tertiary valleys interrupting its length. As in Hullcar, the geology comprises two stacked aquifers (Figure 11), the lower of which (OK1) is made up of fine sand to silty sand, with minor gravel, and the upper (OK0) of clean sand to sand and gravel. The two aquifers are separated by a thin semi-continuous layer of green-grey to blue clay to sandy silt. Overall this unit composes between zero and 40% of the overall stratigraphic thickness, but is generally around 15-20% of the overburden thickness. Although relatively continuous through much of the valley (Figure

4 and Figure 5), at the outlet to the Okanagan Valley, this unit pinches out resulting in substantial hydraulic connection between the upper and lower aquifer below Grandview Flats. Elsewhere in the O'Keefe Valley the composition of the unit has higher proportions of sand, which may result in local higher connectivity between the two aquifers. Both the aquifers and the intervening confining unit are compacted and/or cemented in places. The confining unit is known to contain shells indicative of interglacial conditions during deposition.

The two aquifers and the intermediate confining unit straddle the same stratigraphic periods as the Hullcar Valley, ranging from post-Okanagan center glaciation through late Fraser glaciation. Lower portions of OK0 and upper portions of the confining unit may be partially reworked by glacial movement. The highest point of the valley thalweg is lower than the equivalent point in the western portion of the Hullcar Valley, and contains several kettle lakes that are larger than Parkinson Lake in the Hullcar Valley. This suggests that Hullcar was the first valley to be ice free, followed by the O'Keefe Valley shortly after. The unconfined aquifer in the O'Keefe Valley and its downstream fan below Grandview Flats is substantially thicker than the equivalent HC0 aquifer and its fan below Deep Creek, although the valley is somewhat narrower. Once the Lower Salmon River Valley was opened up, the Lower Salmon River was diverted onto its current course north from Glenemma, and flow through the O'Keefe Valley ceased. Unlike Hullcar, through which Deep Creek continued to flow after the Fraser glaciation, no surface water flowed through the O'Keefe Valley once the Lower Salmon River found its current course. Thus, the valley has not been substantially affected by subsequent erosion or sedimentation since the last glacial recession.

Like the Hullcar Valley, a bedrock topographic high resides close to the entrance of the O'Keefe Valley (Figure 11) at a higher elevation than the Lower Salmon River which prevents lateral groundwater recharge from the main valley. Most of the discharge from the O'Keefe aquifers is to the Okanagan Valley through the fan below Grandview Flats.

The average static water levels for wells in these aquifers are some of the deepest for the study area. The average water depth recorded for OK0 is 19.6 m-bgs and for OK1 is 56.5 m-bgs. Average yields from these wells are mid-range for the study area: 2.5 litres per second (lps) for OK0 and 3.1 lps for OK1.

4.5 Tuhok Valley

Like the preceding two secondary valleys described above, two aquifers have been delineated in the Tuhok area (Figure 12), a lower basal aquifer (TH1) and an upper unconfined aquifer (TH0). These aquifers are semi-continuous within the valley (Figure 4, Figure 5 and Figure 12) and generally much thinner than their counterparts in the Hullcar and O'Keefe Valleys. TH1 is composed of clean gravel with lesser coarse sand, and TH0 is medium to coarse sand and gravel. These aquifers may be compact in places. The lower unit is generally confined by a red to blue-grey silt, clay or till layer, which may be compacted and/or cemented. Overall the Tuhok Aquifers appear coarser grained, and the confining unit finer-grained than equivalent units in the Hullcar and O'Keefe Valleys. Development of till in the valley appears more substantial than in the Hullcar or O'Keefe Valleys. Stratigraphy is also significantly more complicated, aquifer layers are not massive, but generally alternate with finer grained layering, and can pinch out and reappear across and along the length of the valley.

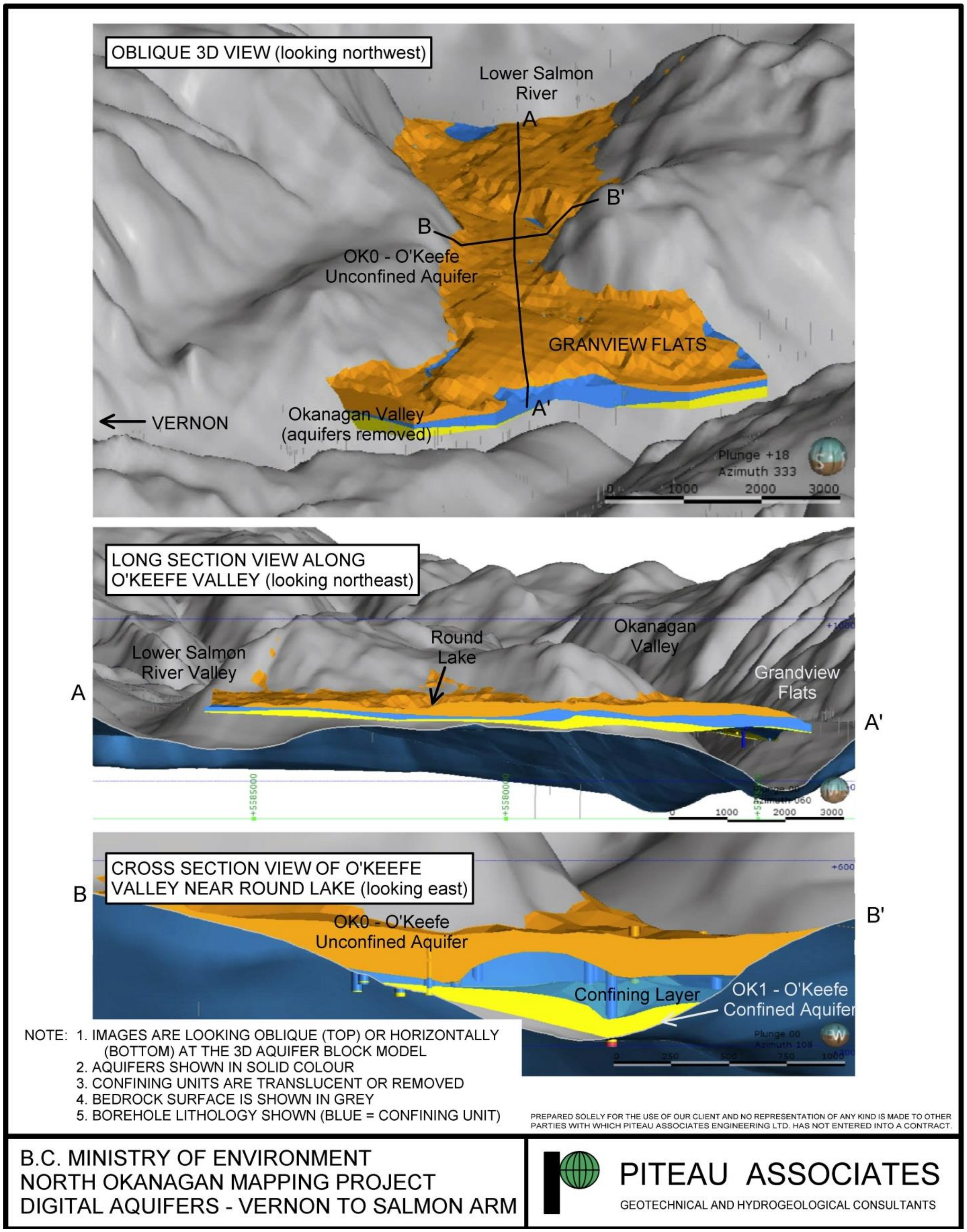

Figure 11: Model views from Leapfrog of the O'Keefe Aquifers.

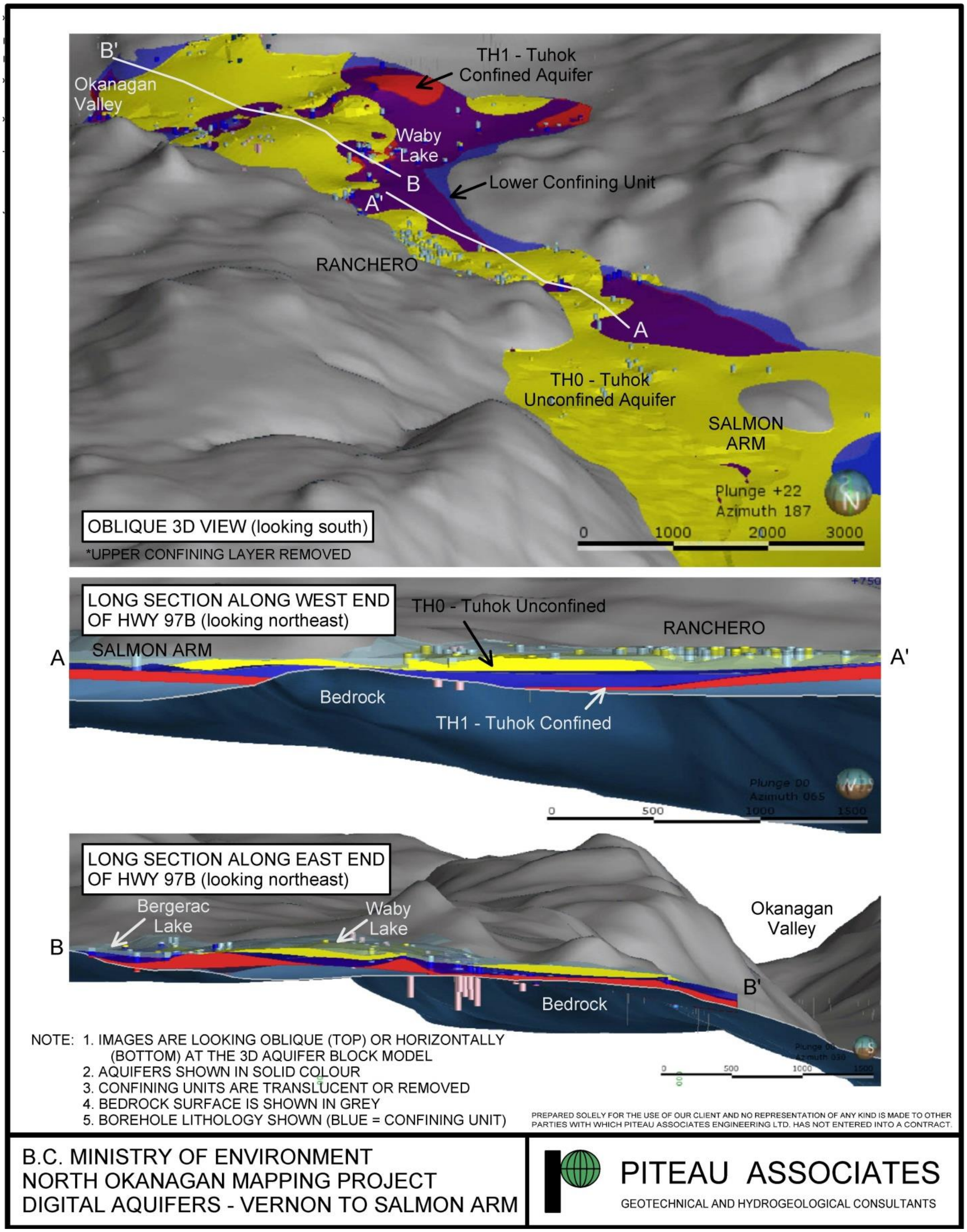

Figure 12: Model views from Leapfrog of the Tuhok Aquifers.

The central, and narrowest, portion of the valley is characterized by low-lying bog, marsh and several kettle lakes (including Bergerac Lake), which are indicative of late ice blockage in the valley. The overall topographic gradient in the valley is from northwest to southeast, yet the head of the valley is situated 200 m above the level of Shuswap Lake. As ice was receding from the Tuhok Valley, Salmon Arm and the Shuswap Valley must have remained filled by a large glacier, a portion of whose meltwater likely flushed down the Tuhok Valley towards the Okanagan Valley. Despite the abundance of coarse sediment being deposited as the Tuhok aquifer, there is no alluvial fan at the outlet of the valley, as at the outlet of Deep Creek and below Grandview Flats. Likely, this portion of the Okanagan Valley was still ice-filled, redirecting that water and dispersing its sediment load to the south along the Okanagan Valley towards Enderby.

Like both the Hullcar and O'Keefe Valleys, there is a significant bedrock topographic high below the base of the valley south of Salmon Arm (Figure 12), which prevents lateral recharge from the north. Groundwater discharge from this valley is mostly to the east into the Okanagan Valley, with some discharge to overburden to the west through upper Deep creek, across a small groundwater divide that likely resides west of Waby Lake.

The average depth to water in TH0 is 16.6 m-bgs, and in TH1 is 21.2 m-bgs. The average well yield reported from wells in TH0 is 1 lps and in TH1 is 2 lps. However, the well density in the valley is high compared to the study area, with 6 wells/square km in TH0 and 3 wells/square km completed in TH1. Land use, average well yields, and well density are consistent with rural-residential, and to a lesser extent agricultural groundwater use, as the primary utilization of the aquifers in the area.

4.6 Ashton Creek

In contrast to the larger, valley-filling aquifers dominating overburden in the main and secondary valleys, the tertiary valleys of the Shuswap River east of Enderby, and BX Creek, east of Vernon, host aquifer sediments deriving from erosion of local hillslopes forming the walls of the valleys. Below and west of the community of Ashton Creek are two sand and gravel aquifers separated by an intermediate grey-blue clay, to silty clay and possibly till confining unit (Figure 13). The lower aquifer (AC1) steeply blankets the northern bedrock slope of the valley below overburden cover, between the mouth of the valley near Enderby and Ashton Creek, and across the valley under the Shuswap River. The full extent of the aquifer is poorly defined due to limited well development in the valley. In contrast, the upper aquifer is wedge-shaped, forming the relatively flat topography of the valley north of the Shuswap River, over a slightly smaller footprint than the underlying aquifer.

Both aquifers are thickest below, and appear to fan out radially from the mouths of Ashton Creek and Brash Creek, situated on northern slopes of the valley (Figure 13). The geometry and composition of these aquifers is consistent with alluvial fans formed by outwash from current and previous generations of these valleys. Current streamflow and sedimentation are relatively quiescent, suggesting that the bulk of the sedimentation likely occurred during or closely following glacial recession when potential streamflow and upstream sediment erosion would have been greatest. The Shuswap River may partially cut down through the unconfined aquifer AC0, and may be hydraulically connected to it.

The underlying confining unit appears to pinch out close to the outlet of Ashton Creek and Brash Creek, thus the two aquifers may be hydraulically connected at these sites, and may receive much of their recharge from the creeks. The lateral extent of these aquifers is not well defined. However, given that they appear to be formed as local alluvial fans centered on Ashton and Brash Creek, unless there are additional fans not identified close by, the aquifers may not be well connected to groundwater that could potentially move into the valley from the direction of Mabel Lake in the east, or out of the valley to Enderby in the Okanagan Valley.

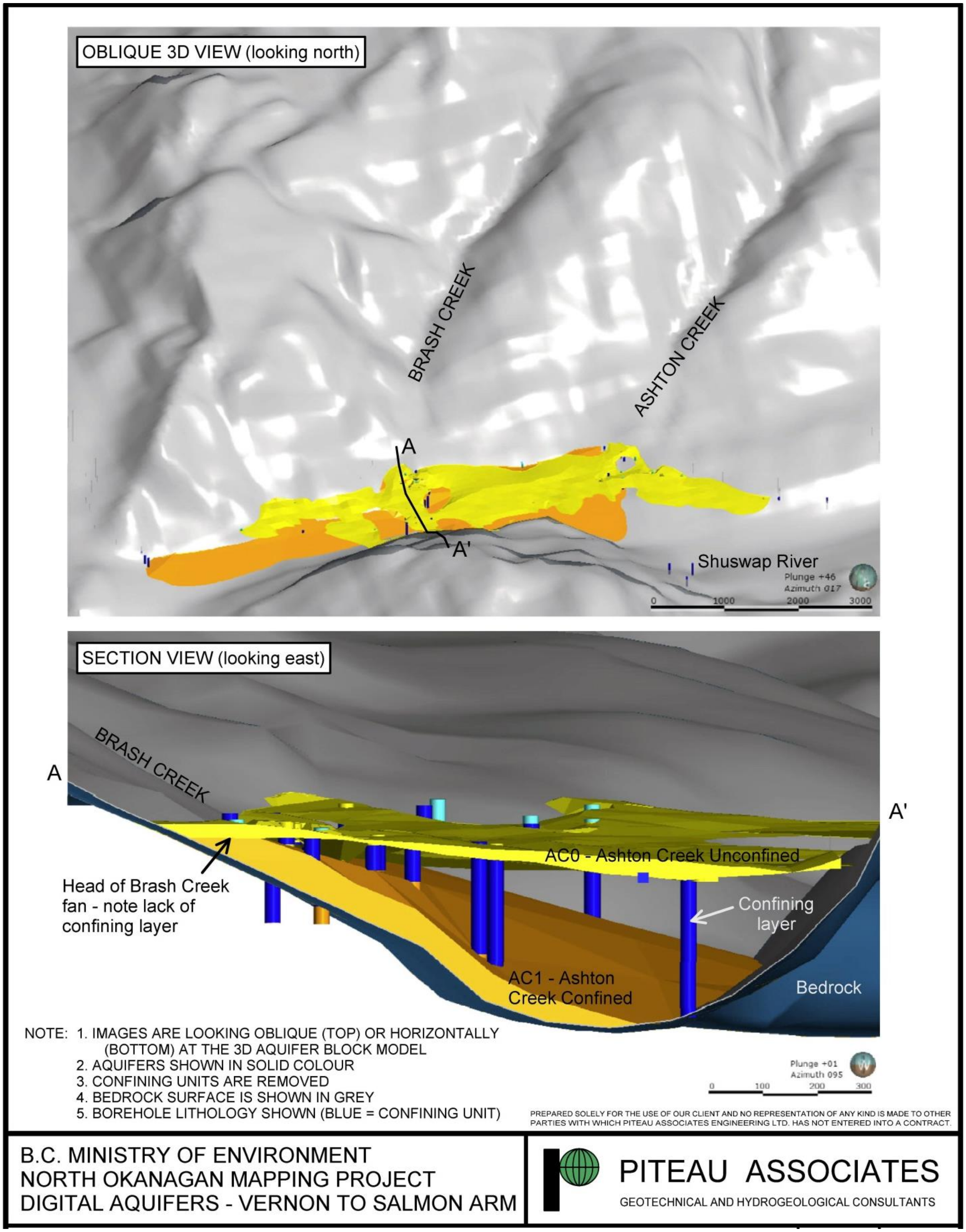

Figure 13: Model views from Leapfrog of the Ashton Creek Aquifers.

Average well yields are moderate; wells in AC1 average 3 lps and in AC0 average 2 lps. The density of wells in the upper aquifer is high at about 4 wells/square km, however the lower aquifer is significantly less utilized with 1 well/square km. The average depth to water in AC1 is less than in AC0 (6.8 m-bgs versus 9.8 m-bgs), suggesting that the confining unit may be creating upward gradients in the aquifer, and/or the upper aquifer is well drained.

4.7 BX Creek

A single relatively continuous aquifer is mapped near the base of overburden, blanketing the buried north bedrock slope above upper BX Creek (Figure 14). This sand and gravel aquifer is predominantly confined, and is overlain by grey-blue clay and till which may be locally compacted or cemented. Organics, including wood, are noted in silty sand below coarser grained aquifer sediments in borehole logs. This aquifer is interpreted to be pre- to early- glacial alluvium and colluvium derived from a limited upslope catchment. The aquifer sediments continue below BX Creek where the valley narrows to a thin channel above Vernon, and is likely related to fan material that extends out as a confined aquifer beneath the main valley under Vernon. There may be some hydraulic connection between the two aquifers under confined conditions. The relative difference in elevation between these two aquifers is likely responsible for elevated pore pressures and local artesian conditions in the main valley.

The average yield of wells completed in the BX Aquifer is 1.2 lps, very low in comparison to the rest of the study area. In contrast, density of wells completed in the aquifer is extremely high with 13.5 wells/square km. Although reliance on the aquifer appears high, land use suggests that most groundwater use is domestic and therefore likely lower demand per well than other aquifers in the study area.

4.8 Hullcar Perched Aquifers

A unique aquifer feature defined as the Hullcar Perched Aquifers reside under hill slopes surrounding the intersection of Deep Creek and the Hullcar Valley (Figure 4). Below these slopes small pockets of gravel, sand and gravel, and silty sand are interpreted to fill depressions eroded into the top of a basal till that overlies shallow bedrock. These aquifers are probably hydraulically disconnected from each other and from the Hullcar aquifers HC0 and HC1 due to their relative elevation below the hillslopes surrounding the main valley. They provide an important local source of groundwater for properties in the area, and thus warrant recognition, particularly given the current interest in studying the Hullcar area. These aquifers are generally confined by overlying clay to silty sand, but may be unconfined.

The average yield of wells completed in these aquifers is 2 lps, however this average is skewed by a few individual higher producing wells. The median yield, which is likely more representative, is 1 lps. The average water depth observed was 18 m-bgs, but ranged between 1-44 m-bgs. Long-term groundwater storage is inferred to be low, due to the limited size of the aquifers and their catchments. These are inferred to be recharge limited, likely receiving water only from direct precipitation, and thus water levels are likely to fluctuate significantly with seasonal and longer-term climate cycles.

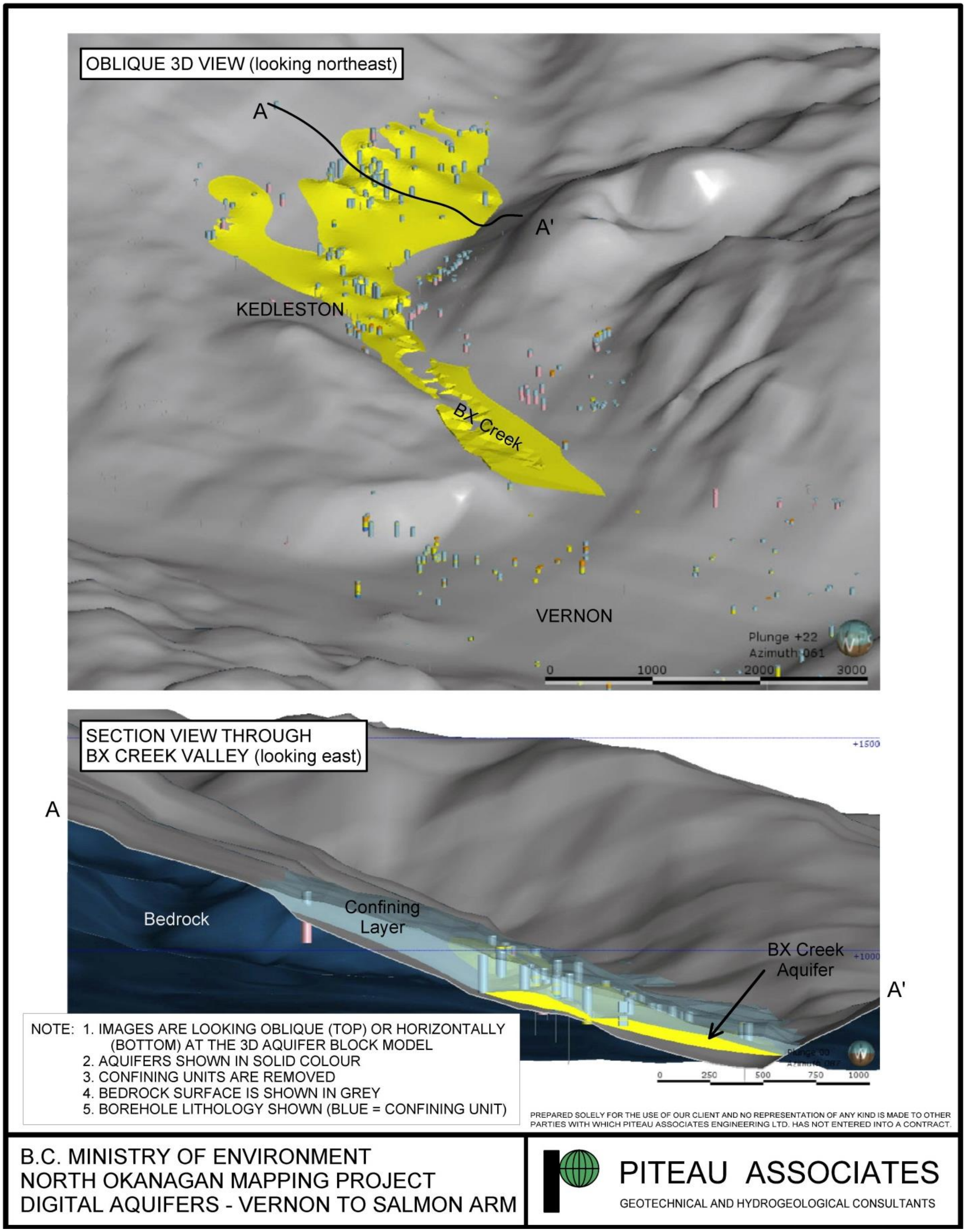

Figure 14: Model views from Leapfrog of the BX Creek Aquifer.

5. DATA GAPS AND UNCERTAINTY

The identification of key stratigraphic units/sequences and the reconciliation of aquifer limits has been undertaken using available geological mapping, geophysical profiles and borehole information. The number of data points, including spatial variability and density, contributed significantly to the uncertainty in identifying the thickness and limits of hydrostratigraphic units and aquifer extents. Table 4 presents a qualitative analysis of data gaps and uncertainty, and documents specific points of uncertainty for each named aquifer in this assessment. The table presents a summary of:

- data available for each aquifer: footprint area, number of boreholes, data density, boundaries, thickness;
- the uncertainty associated with type and extent of boundaries and thickness;
- information required to verify, or investigate and resolve the gap; and
- relative importance and priority for undertaking the additional work

Plan maps shown in Figure 15 were compiled to graphically illustrate the relative uncertainty across the study area based on proximity to known data points and sectional interpretations of the bedrock. Maps are based on bedrock data (upper left), wells completed in the unconfined aquifers (upper right) in the shallow (lower left) and deep (lower right) confined aquifers across the region. Inferring from borehole data that most of the overburden in the area hosts some form of aquifer, these illustrations qualitatively illustrate where the density of data (boreholes) is highest and where there are significant gaps in wellbore coverage.

Even with boreholes present, the quality of the digital lithology logs varies significantly. Of the approximately 14,000 lithology data points compiled at the start of the project, 11,600 were found to have useful lithologic information and were retained for the interpretations. Numerous assumptions were incorporated in the completion of this body of work. There is a level of uncertainty in the resulting conceptual hydrogeological model which cannot be quantified because of inconsistent quality in the reporting of geology in borehole data, spatial data gaps and the limitations of the software used for 3D interpretation. The scale of the models also limits the resolution of local interpretations and compliance of the model contacts with lithology interpretations from well logs. As more information becomes available, this work should be updated.

Using lithology to understand aquifer boundaries leads to additional uncertainty; the transition from aquifer to non-aquifer composition may be subtle and/or gradual. Best efforts were made to establish boundaries where soil composition is of sufficient contrast to develop distinct flow regimes (confining unit versus transmissive unit). However, some boundaries are distinctly transitional, either in grain size gradation (e.g., sand grading through silty sand to sandy silt), or in alternating lithologies (e.g., gravel transitioning through interlayered gravel and clay to clay). Boundaries with gradational grain size are present in the Hullcar Aquifers, the Spallumcheen segment of the Okanagan Valley Aquifers, and the Lower Salmon River Aquifers. Boundaries defined by complex alternating lithologies are present in the BX Creek, Tuhok and Unconfined Okanagan Valley Aquifers.

The unconfined aquifers in the study area can have varying degrees of local confinement, which can change their hydraulic character. The thickness and extent of confinement at surface and between aquifers at depth is difficult to model based on boreholes alone. Surficial geology maps developed by Fulton et al (1974a and 1974b) were used to help refine the boundaries of the unconfined aquifers and to understand the nature of any overlapping strata.

Table 4: Well density, aquifer uncertainty and recommendations.

Aquifer				Wells		Uncertainty Description	Uncertainty Ranking[1]	Information Required[2]	Recommended Investigations[3]
Location	Code	Type	Area (km²)	No. of Wells	Density (No./km²)				
Ashton Creek	AC0	UNC	8.1	30	3.7	- portions of this unit may be unsaturated - full extent of deposits upstream and downstream in valley not well defined	Good	WTG	WLA, surficial mapping
Ashton Creek	AC1	CON	13.5	15	1.1	- unknown hydraulic connection with AC0 (portions unconfined?) - depth and lateral continuity	Fair	PSG; VHG; HHG	WLA; drilling or geophysical survey to define aquifer extent
BX Creek	BX1	CON	9.6	142	14.8	- internal continuity is poorly defined - sediments are poorly sorted and bedding is likely discontinuous	Good	PSG; VHG; HHG	WLA
Hullcar	HC0	UNC	21.7	70	3.2	- unclear how much of this unit is unsaturated - may be hydraulically connected to lower Salmon River aquifers across a groundwater divide (no wells across this divide) - uncertain if HC0 or HC1, or both, extend below upper deep creek	Good	WTG	WLA; surficial mapping/ sampling
Hullcar	HC1	CON	15.1	64	4.2	- boreholes and hydraulic gradients (Golder, 2017) suggest that there may be windows through the overlying confining layer; insufficient deep boreholes to confirm - stratigraphic orientations suggest this unit may be genetically and hydraulically linked to the former Deep Creek/ Sleepy Hollow unconfined fan aquifer, however insufficient borehole coverage at the transition in slope separating the two	Fair	PSG; VHG; HHG; hydraulic properties (conductivity) and extent of confining unit	WLA; drilling/testing in areas of hydrostatic gradient and uncertain extent of confining unit
O'Keefe	OK0	UNC	23.9	41	1.7	- lower contact of this unit is poorly defined in places	Good	WTG	WLA; surficial mapping
O'Keefe	OK1	CON	17.6	36	2.0	- the extent of the confining layer is uncertain, there may be significant hydraulic connection to unconfined aquifer - where this layer is absent, the contact between upper and lower aquifer is not well defined as they are similar composition	Fair	PSG; VHG; HHG; hydraulic properties (conductivity) and extent of confining unit	WLA, drilling/testing in areas of hydrostatic gradient and uncertain extent of confining unit

Aquifer				Wells		Uncertainty Description	Uncertainty Ranking[1]	Information Required[2]	Recommended Investigations[3]
Location	Code	Type	Area (km^2)	No. of Wells	Density (No./km^2)				
Spallum-cheen	OR0-A	UNC	101.1	110	1.1	- unit appears to be regionally continuous, but the thickness of the aquifer relative to its size limits the ability define the unit in 3D - saturated portions of the aquifer may be discontinuous strata is locally complex due to transition from hillslope derived deposits along margins to lower-energy deposition in the valley center	Fair	WTG; increased refinement of local scale geology	WLA; surficial mapping/ sampling; re-analysis of well logs, looking at distribution of sub-aquifer grade materials and improve criteria defining unit
Swan Lake	OR0-B	UNC	7.9	9	1.1	- aquifer appears thinner	Fair	WTG	WLA; surficial mapping
Vernon	OR0-C	UNC	21.1	10	0.5	- aquifer sediments may be continuous, but unsaturated	Fair	WTG	WLA; surficial mapping
South Vernon	OR0-D	UNC	14.7	65	4.4	- well density is very localized, unclear how extensive aquifer sediments and saturated formation are - uncertain hydraulic connections with the Coldstream valley and Vernon area	Good	WTG	WLA
Eagle Rock	OR0-E	UNC	7.7	78	10.1	- this alluvial fan aquifer likely spans multiple equivalent age aquifers in the main valley - suggests that it may be a significant source of recharge to lower aquifers in the valley, but this relationship is poorly defined	Good	WTG	WLA
Mara	OR0-F	UNC	3.5	19	5.4	- this alluvial fan aquifer likely spans multiple equivalent age aquifers in the main valley - suggests that it may be a significant source of recharge to lower aquifers in the valley, but this relationship is poorly defined	Good	WTG	WLA
Spallum-cheen	OR1-A	CON	134.4	271	2.0	- as with the overlying unconfined aquifer, the scale of the valley is large compared to the thickness of the unit and width of the valley, making 3D interpretation difficult - limited understanding of the depth extent and lateral continuuity of the unit in places - uncertain hydraulic connection with thickened	Fair	PSG; VHG; HHG; hydraulic properties (conductivity) and extent of confining unit	WLA; re-analysis of well logs, looking at distribution of sub-aquifer grade materials and improve criteria defining unit

Aquifer				Wells		Uncertainty Description	Uncertainty Ranking[1]	Information Required[2]	Recommended Investigations[3]
Location	Code	Type	Area (km²)	No. of Wells	Density (No./km²)				
						alluvial fan deposits (Mara, Eagle Rock etc) which appear to span the age and thickness of this aquifer - can be difficult to differentiate locally confined portions of the upper aquifer (OR0) and shallow portions of the confined aquifer (OR1)			
Swan Lake	OR1-B	CON	13.8	26	1.9	- unknown how extensive/continuous this unit is below Swan Lake	Fair	PSG; VHG; HHG; hydraulic properties (conductivity) and extent of confining unit	WLA; drilling below Swan Lake to assess hydraulic connection and aquifer continuity
Vernon	OR1-C	CON	20	72	3.6	- BX creek aquifer likely has similar origins in terms of sediment provenance - therefore there may be some hydraulic connection, but this is poorly understood - low well density reduces the certainty in the geometry of this aquifer	Fair	PSG; VHG; HHG; hydraulic properties (conductivity) and extent of confining unit	WLA
South Vernon	OR1-D	CON	6.8	54	7.9	- high well density provides reasonable aquifer geometry, but degree of hydraulic connection with neighbouring aquifers is uncertain	Good	PSG; VHG; HHG; hydraulic properties (conductivity) and extent of confining unit	WLA
Spallum-cheen	OR2	CON	77	5	0.1	- deep aquifer, with extremely limited borehole coverage - based on it being an analogue of OR1, it may be extensive throughout the Okanagan Valley, but has not been drilled	Poor	PSG; VHG; HHG; hydraulic properties (conductivity) and extent of confining unit	WLA
Spallum-cheen	OR3	CON	23.1	6	0.3	- deep aquifer, with extremely limited borehole coverage - topography is premissive for this unit to be extensive throughout the Okanagan Valley, but has not been drilled	Poor	PSG; VHG; HHG; hydraulic properties (conductivity) and extent of confining unit	WLA
Lower Salmon	SR0	UNC	29.7	128	4.3	- extensive aquifer along length of valley, with localized borehole density	Fair	WTG; increased refinement of local	WLA; surficial mapping/ sampling;

Aquifer				Wells		Uncertainty Description	Uncertainty Ranking[1]	Information Required[2]	Recommended Investigations[3]
Location	Code	Type	Area (km^2)	No. of Wells	Density (No./km^2)				
River						- sharp facies changes across the valley, from steep hillslope deposits to lower gradient streambed and lacustrine sediments		scale geology	re-analysis of well logs, focussing on unit boundaries
Lower Salmon River	SR1	CON	9.9	22	2.2	- deep aquifer, with limited borehole coverage	Poor	PSG; VHG; hydraulic properties (conductivity) and extent of confining unit	WLA; re-analysis of well logs, focussing on unit boundaries; drill to base of overburden near Northern and Southern limit of valley
Tuhok	TH0	UNC	25.4	149	5.9	- strata varies in thickness with complicated stratigraphy - some layering may be discontinuous or subject to facies changes	Fair	WTG; increased refinement of local scale geology	WLA; surficial mapping/sampling; re-analysis of well logs, focussing on unit boundaries
Tuhok	TH1	CON	27.1	81	3.0	- strata is thin with complicated stratigraphy - some layering may be discontinuous or subject to facies changes	Poor	PSG; VHG; HHG; hydraulic properties (conductivity) and extent of confining unit; local geological refinement	WLA; re-analysis of well logs, focussing on unit boundaries

Notes:
1 - Uncertainty is ranked loosely based on the relative quality, quantity and density of drilling data present within an aquifer.
2 - Information required may include water table geometry (WTG), piezometric surface geometry (PSG) , vertical and/or horizontal hydraulic gradient (VHG, HHG respectively).
3 - Recommended investigations may include a water level assessment (WLA) comprising a study of the existing water level database, surveying of water levels in borehole and collection of well level data over longer term periods from selected monitoring wells

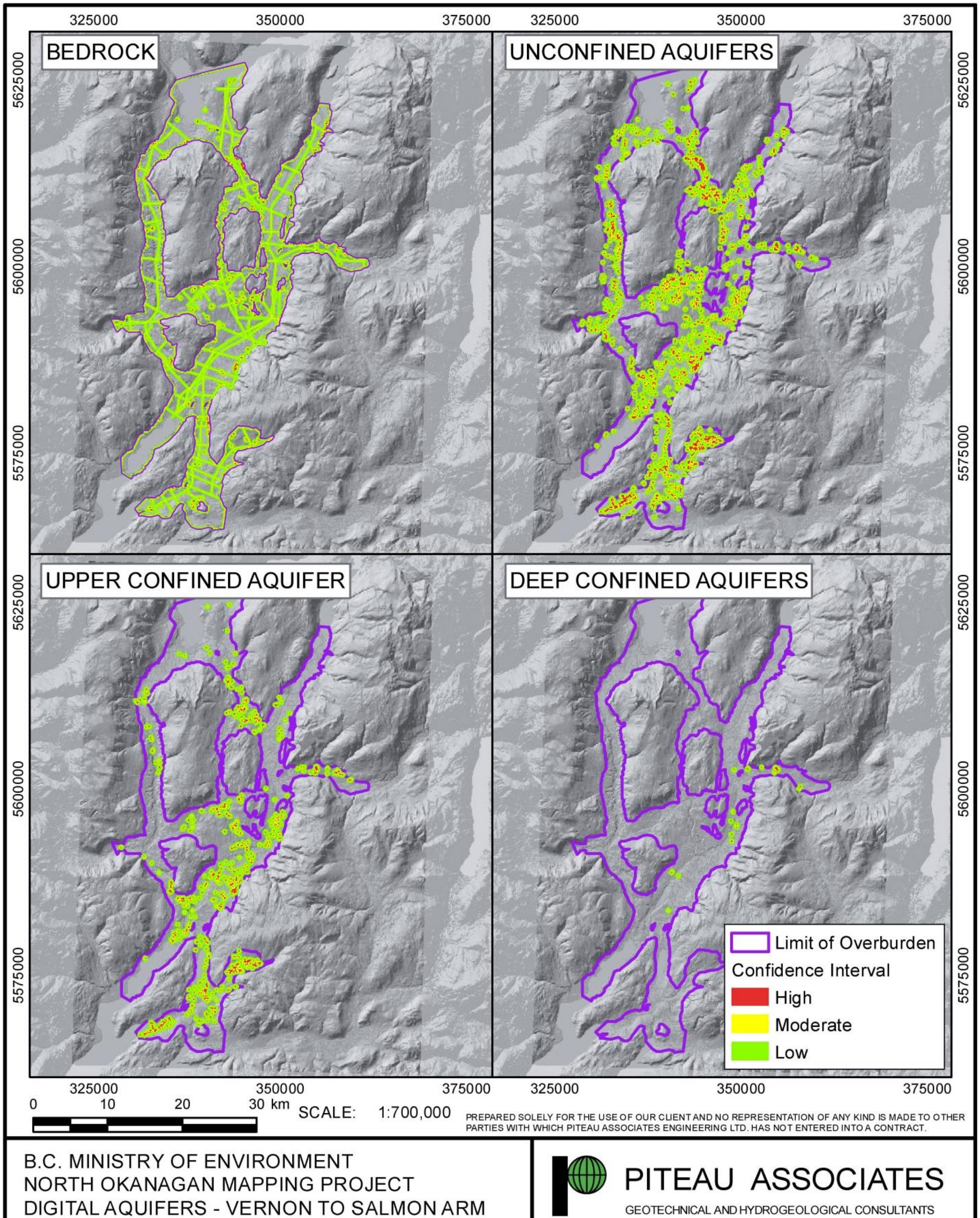

Figure 15: Data density for bedrock and aquifer interpretations.

Several issues were identified during digitization of the aquifers for this assessment, which affected the quality of the interpretations generated by the Leapfrog™. In MAIN valleys, the scale of the aquifer thickness (metres) is extremely small in comparison to the aquifer extent (kilometres). Where the aquifer tended to be particularly thin, Leapfrog™ weighted models towards the more dominant, thick, fine-grained units and did not extend the aquifer unit to these locations. Therefore, despite the conceptual interpretation that the unconfined and confined aquifers are likely quite continuous across and along the Okanagan and Lower Salmon River Valleys (Figure 4), Leapfrog™ tended to only include aquifers in areas of substantial thickness, pinching out in areas where the aquifer is thin, or data is sparse.

Similarly, the models did not always honour important fine-scale detail such as local pinching out of confining units which expose units to unconfined conditions, or over-thicken confining units at surface where an individual borehole might suggest a local window to the aquifer exists.

In instances of extremely sparse data, such as the deep (OR2) and basal (OR3) Okanagan Valley Aquifers, minute changes in the interpreted orientation of bedding result in poor interpretations where contacts are extrapolated out to significant distances away from known data points. In these cases, models were limited to areas within reasonable proximity to existing data points.

Implicit modelling to an extent can increase the quality of a 3D model by incorporating contact trends, and groups of borehole contacts to define aquifer boundaries. Such extrapolation introduces apparent uncertainty where boreholes do not match the implicit interpretation, whereas in an explicit model this would not be apparent. However, the model presented here represents the current best interpretation of all available data, which is a significant improvement over previous models which were based on a more limited dataset.

6. CONCLUSIONS, DISCUSSION AND RECOMMENDATIONS

This assessment attempts to provide a coherent regional interpretation of the geometry and hydrogeologic relationships of the various aquifers in the North Okanagan area. Based on analysis of the hydrostratigraphy (i.e., the distribution of aquifer sediments in relation to non-aquifer, or potentially confining soils), the geology of the North Okanagan aquifers is remarkably consistent within valleys of similar size and geometry, despite having an apparently complex geologic history. The consistency and the continuity of the aquifers have important implications for the interpreted hydrogeology of the various aquifers, although some uncertainty persists. Three basic valley types have been identified, including MAIN (Okanagan, Lower Salmon River), SECONDARY (O'Keefe, Hullcar and Tuhok) and TERTIARY (Ashton Creek, BX Creek) valleys.

6.1 Summary of Aquifer Assemblages

The main valleys comprise both a shallow unconfined and confined aquifer limited to depths of between 10-100 m, which support most of the local groundwater supply needs. These shallow aquifers are relatively continuous and originate from either pre-glacial alluvium, or late to post-glacial outwash. At least two deeper aquifers were also identified in a limited number of deep boreholes in the Okanagan Valley. The extent of the deeper aquifers is uncertain. Current aquifers mapped by the B.C. ENV in the Okanagan Valley were found through this assessment to be contiguous and therefore the boundaries are not justified from a hydrostratigraphic perspective. Furthermore, based on this stratigraphic continuity, they are also likely hydraulically connected as well. However, previous aquifer boundaries denoted by B.C. ENV aquifer number have largely been retained, with modest revisions, to assist in management of groundwater resources in the area.

The margins of the main valleys are characterized by numerous discrete coarse-grained fans formed through accumulation of alluvium originating from small side valleys. These fans likely contribute significant groundwater recharge to the finer grained aquifer segment below the valley floor, commonly developing artesian conditions. The local fans are hydraulically well-connected to both unconfined and confined valley-centered aquifer segments, which are regionally more extensive, and are an integral part of the hydrostratigraphy of the main valleys.

The Mara Lake and Eagle Rock fans are hydrostratigraphic continuations of the Okanagan Valley Unconfined Aquifer, but are retained as unique aquifer segments due to their substantial size and capacity. The outlet of BX Creek below Vernon likely hosts a similar fan, but it is more dispersed and indistinguishable from alluvium comprising the aquifer that extends across the valley floor. Fans below Deep Creek (Sleepy Hollow) and Grandview Flats are analogous, however are spatially more closely related to, and hydraulically connected with, aquifers upstream in the Hullcar and O'Keefe Valleys, respectively.

The secondary valleys of O'Keefe, Hullcar and Tuhok were found to host thicker and coarser-grained aquifers in comparison to the main valleys, however, the overall assemblage is roughly the same. Unconfined and underlying confined or semi-confined aquifers at shallow depths supply all the local groundwater needs for the residents and communities of the valleys. The confined and semi-confined aquifers comprise thick accumulations of in situ and reworked pre-glacial alluvium, while the unconfined aquifers are dominantly composed of late glacial outwash.

Late in the Fraser glaciation when the Lower Salmon River headwaters were ice free, ice blockages forced meltwater to accumulate and periodically flush through the southernmost valleys, and out to the Okanagan Valley, moving and depositing significant volumes of sediment in the process. Ice blockages in these valleys were opened in sequence as the stagnant ice blockages were cleared. The Hullcar Valley was opened first, followed by the O'Keefe Valley and ultimately the Lower Salmon River Valley, which continues to carry runoff north into Shuswap Lake. Sediment composition and the preserved geomorphology of the valleys indicate that flooding events were likely rapid inundations of high volumes of sediment and water (possibly seasonal jökulhlaup), with little time to develop channels and other features that indicate sustained flow of surface water. The Tuhok Valley also saw significant periods of outwash from meltwater accumulated next to glaciers at Salmon Arm, however the thickness of resultant aquifers is limited in comparison, and complexly interlayered with glacial till and lacustrine deposits that fill the valley.

The extent and thickness of the intervening confining unit found in the three secondary valleys varies. However, this unit is substantially thinner than the equivalent hydrostratigraphic unit observed in the main valleys. In the secondary valleys, the confining unit is also generally discontinuous, and is inferred to allow locally unconfined conditions to exist within the lower aquifers.

All three valleys appear to have significant bedrock highs associated with their westernmost extents near the Lower Salmon River Valley. This feature is inferred to generate a groundwater divide that prevents groundwater from entering the secondary valleys from the Lower Salmon River Valley. Thus, groundwater recharge to these valleys is limited to lateral recharge from local upland areas. Most discharge is to the Okanagan Valley via alluvial fans at the mouth of the valleys, or through bedrock.

The remaining tertiary valleys are dominated by local hill slope processes that formed the Ashton Creek and BX Creek Aquifers. Both appear to have been formed by accumulation of alluvial sediments or colluvium at or near the base of the valley. At Ashton Creek, two distinct alluvial fan aquifers formed from the amalgamation of alluvial fans deposited at the mouth of Ashton Creek and Brash Creek, one likely prior to the Fraser glaciation, the second likely in the late to post-glacial period. While the BX

Creek Aquifer may be genetically related to sediments comprising the aquifer below Vernon, both BX Creek and the Ashton Creek Aquifers appear to be disconnected or of limited connection hydraulically to the adjacent Okanagan Valley.

6.2 Geological History

Consistent with the geological history of the northwestern part of North America, the North Okanagan was subjected to multiple glacial episodes spanning the Pre-Wisconsin, Early/Middle Wisconsin, Olympia (non-glacial), and Wisconsin/Fraser periods. The lowermost stratigraphy filling the valley bottom is interpreted to be a mix of glacial and interglacial sediments of uncertain Pleistocene age (Pre-Wisconsin). These deepest units are defined as Pre- or early Wisconsin in age, primarily based on the presence of organic material and were not addressed in this study, but may form aquifers. Overlying these units is a relatively thick unit of lacustrine silts deposited during the non-glacial Olympia (Middle Wisconsin) period. The Pre-Wisconsin and Middle Wisconsin units are relatively continuous in the study area, within the main Okanagan Valley, extending from Vernon to Mara Lake.

The uppermost units in the study area are from the Fraser glaciation (Middle to Late Wisconsin) periods, and are therefore younger. All the aquifers in the area mapped by the B.C. ENV are within these shallow units.

The extent and thickness of the relatively shallow units is a function of the orientation and persistence of ice in the base of the valleys, the deposition resulting from sediment laden meltwater flow into the valleys and along the edges of the ice, and the extent of large glacial lakes.

The uppermost portion of the Bessette sediments from the Olympia non-glacial period was eroded during the advance of the Fraser Period glaciers. The re-worked sediments resulted in an extensive regional aquifer. Glacial lakes began to form around the perimeter of ice that remained in the valleys. Meltwater channels developed on the edges of the ice and runoff from the exposed upland areas created ice contact and fan deposits at locations where smaller valleys intersected the main valleys. Hullcar and Deep Creek north of Hullcar, including the Gardom Lake area, were the first to be exposed. Runoff from the edges of remnant ice deposited alluvium in these areas, which formed localized aquifers. Ice was stagnant during this period along the Tuhok Valley and within the Lower Salmon River Valley. At the same time, significant ice was still present along the Okanagan Valley, covering present day Lake Okanagan, Vernon, Armstrong, Enderby, Mara and Salmon Arm.

Glacial Lake Penticton continued to grow and eventually extended to a point northeast of Armstrong and to Okanagan Landing southwest of Vernon. Ice was still present in the Okanagan Valley to the north (to Mara), to the south along Lake Okanagan, in the Lower Salmon River Valley and in the Shuswap Valley (to the east of Enderby). A portion of Tuhok Valley was exposed and meltwater runoff, which flowed southward towards Gardom Lake and upper Deep Creek (north of Hullcar). Runoff continued in the Hullcar area adding material to the alluvial aquifers. Smaller valleys along the east side of the Okanagan Valley, contribute runoff to the main valley, forming local meltwater channels and ice contact or fan deposits. Aquifers along the edge of the Okanagan Valley that were formed during this period include Eagle Rock and Keddleston/BX. The Mara Aquifer may also have been formed at this time, although there was still substantial ice in the valley at this location.

As additional down-melting occurred, the extent of ice in the main valleys diminished and Lake Penticton occupied the eastern arm of the Valley. This is likely the period when pro-glacial deposits resulting from ice retreat formed adjacent to Grandview Flats near Otter Lake and Swan Lake. Meltwater runoff along the Tuhok Valley was to the south towards Gardom Lake, where ice contact, or fan deposition occurred as ice was still present in the Okanagan Valley from Enderby to Mara.

Continued runoff from glaciers and uplands provided sediment for deposition of other ice contact, fan and meltwater channel deposits along the edge of the Okanagan Valley. The Lower Salmon River Valley was still completely under ice.

Eventually, all ice was gone except within the Lower Salmon River Valley and north of Grindrod in the Okanagan Valley. Runoff within the Shuswap Valley was westerly towards the Okanagan Valley via Enderby. Ice was still present in the Lower Salmon River Valley. It is unclear how significant the runoff contributions were to the east (Hullcar) and south (Grandview flats) from the melting ice in the Lower Salmon River Valley. Kettle Lakes in the Lower Salmon River Valley, located immediately south of Glenemma (Heart and Round Lakes), infer the stagnant ice was more to the south and that significant meltwater was transported to the east into the Hullcar area supporting the development of aquifers in the area.

The recession of ice to the north via Mara resulted in the lowering of the water level and reduced the footprint area of the Lake and a portion of the Okanagan Valley between Armstrong and O'Keefe being above water. The size of Lake Penticton continued to decrease and the distance between the lakes increased. Overland flow was from north to south along the valley, from Lake Shuswap to Lake Penticton. The final extent of Lake Penticton was approximately the same as present day Lake Okanagan. Ultimately, the catastrophic failure of the ice dam at McIntyre Bluff, south of Penticton, caused Lake Penticton to drain.

Following glaciation, climate variation was relatively subtle and changes were more frequent. The upper portion of alluvium within the base of the valleys was modified by flooding and drainage, resulting in shallow fluvial deposition of re-worked materials. Aggradation of fan deposits along the edges of the valleys continued. The current terrain and geomorphology of the study area has remained substantially unchanged since the end of glaciation.

6.3 Uncertainty:

Uncertainty in the interpretations presented can originate from the following:

- lack of or insufficient density of borehole coverage (spatial density as well as depth);
- incorrectly located boreholes;
- absent, incorrect, inconsistent or inadequate lithology descriptions
- incorrect depths assigned to borehole lithology intervals;
- outliers, or prior bias skewing explicit interpretations;
- scale/resolution limitations of the model; and
- incomplete understanding or preservation of depositional events

The most significant uncertainty that remains following this assessment is an understanding of the presence and degree of vertical hydraulic connection between aquifers in the study area. This uncertainty stems from two distinct issues:

1. Borehole data is sparse across much of the area and may not adequately delineate the shape and area of windows through confining units, which either cap the valley-filling sediments, or separate stacked aquifers.
2. Soil composition is not adequately described to assess the relative hydraulic conductivity of aquifer units relative to confining units.

Uncertainty is particularly acute in the secondary valleys where the unconfined aquifers are heavily utilized and exposed to surface recharge and potential contamination over a relatively large area.

Additional remaining uncertainty is that the definition of an aquifer is a saturated geologic unit that is sufficiently permeable to yield water in a usable quantity. This assessment sought to delineate hydrostratigraphy with the potential to form a significant unconsolidated aquifer (i.e., sand or coarser granular soils below the valley floor). Incorporation of water levels in this assessment was limited to analysis of average levels, rather than assessment of discrete gradients within or between aquifers.

6.4 Recommendations

The scale and scope of the assessment presented in this report was sufficient for delineating broad hydrostratigraphic trends. The aquifer assemblages have been sufficiently resolved in many of the valleys, where the scale of the aquifer extent versus aquifer thickness, and quantity of data were permissive. The 3D models of the Okanagan Valley, Lower Salmon River Valley and Tuhok Valley require additional work to be more inclusive of existing borehole data, and better refined at smaller scales. If warranted to mitigate groundwater management concerns, a smaller scale analysis of discrete portions of the aquifers, and more detailed mapping are required to improve the overall 3D digital model of aquifers in these valleys. In conjunction with this digital enhancement, stratigraphic relationships could be improved with age dating of organic materials contained within exposed strata, and encountered within new deeper boreholes drilled in the region.

In areas of elevated interest with respect to water management and water use, wellhead surveys should be conducted to verify the location of boreholes in key locations. Boreholes may include those with the most representative stratigraphy, deepest penetration with lithology descriptions and/or with descriptions indicating the presence of windows through confining strata.

An initial study of the existing water level database should be conducted in the context of the revised 3D aquifer geology models. The goal of this study would be to assess approximate limits of saturated aquifer sediments, probable hydraulic gradients and piezometric relationships between aquifers. Measurement accuracy, reliability, time of year and year of measurement is expected to impart considerable error in assessing this data. High priority targets for assessing groundwater levels include:

- O'Keefe Aquifers (Round Lake and Grandview Flats)
- Tuhok Aquifers (Salmon Arm, Ranchero and Waby Lake)
- Ashton Creek Aquifers
- Okanagan Valley Aquifers (Armstrong, Enderby, Okanagan Landing, Vernon)

This initial assessment should be followed by a detailed field study of water levels in surveyed wells in areas of elevated interest. A set of key wells should be delineated that can be measured as a global set over a short period of time; once during the low level of the year (fall) and again during peak levels (spring freshet). These data would be used to assess hydraulic gradients across, as well as between, aquifers. Where permissible, dataloggers should be installed in key boreholes that would have a minimum interference from pumping, to collect a longer-term continuous set of water level measurements, at a high frequency (>8/day). If possible, these monitoring wells should be incorporated into the provincial groundwater observation well network. The objective of this portion of the study would be to assess the character of response to seasonal stresses (recharge and evaporation), as well as diurnal stresses (barometric fluctuations) to further refine the understanding of the local hydraulics of the aquifer around individual wells.

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APPENDIX A: AQUIFER WELL COMPLETIONS AND WELL SUMMARY SHEETS

Information on the well-aquifer completions is provided in a separate Excel file. The data included in this appendix has been used to update the BC ENV WELLS Database. Well Summary sheet information corresponding to the identified well tag numbers (WTN) is accessible through WELLS database (https://a100.gov.bc.ca/pub/wells/public/indexreports.jsp) and EcoCat (https://www2.gov.bc.ca/gov/content/environment/research-monitoring-reporting/libraries-publication-catalogues/ecocat).

APPENDIX B: AQUIFER SUMMARY SHEETS AND SHAPEFILES

Aquifer worksheets and outlines associated with this project are available online from the BC ENV and can be accessed through the WELLS Database (https://a100.gov.bc.ca/pub/wells/public/indexreports.jsp) and iMapBC (https://arcmaps.gov.bc.ca/ess/sv/imapbc/).

APPENDIX C: LIST OF DIGITAL PRODUCTS

Leapfrog Viewer Files:

- Ashton Creek.lfview
- BXCreek.lfview
- Hullcar.lfview
- Okanagan Valley.lfview
- OKeefe.lfview
- Salmon River.lfview
- Tuhok Valley.lfview

The Leapfrog Viewer Files are provided as separate files to the report. A free Leapfrog viewer can be downloaded from ARANZ Geo Limited:
http://www.leapfrog3d.com/products/leapfrog-viewer/downloads