AMEC Environment & Infrastructure
A division of AMEC Americas Limited
3456 Opie Crescent, Prince George, BC
Canada V2N 2P9
Tel +1 (250) 564-3243
Fax +1 (250) 562-7045
www.amec.com

2012 SUBSURFACE DEWATERING SYSTEM
WEST QUESNEL LAND STABILITY PROGRAM

(Volume 1 of 2)

Prepared for:

City of Quesnel
410 Kinchant Street
Quesnel, BC V2J 7J5

Prepared by:

AMEC Environment & Infrastructure
A division of AMEC Americas Limited
Prince George, BC

21 November 2014

KX0439740

EXECUTIVE SUMMARY

In 2012 the City of Quesnel undertook the implementation of a subsurface dewatering system as the first part of a full scale program to reduce groundwater levels and improve land stability in West Quesnel. This report documents the installation of the subsurface dewatering system, the related landslide monitoring system and provides a summary of monitoring data collected to the end of July 2014. Key components of the system include:

- 17 operating pumping wells;
- over 10,000 m of drilled horizontal drains;
- an extensive network of flow metering and groundwater pressure instruments; and
- real-time ground movement instruments.

The pumping wells and the horizontal drains have reduced groundwater pressures in West Quesnel, with the horizontal drains being the most productive. Groundwater pressure reductions in the order of 0.5 m to 14 m attributable to the implementation of the subsurface dewatering system have been observed. Over the period of system implementation, measured landslide related ground movements have been on the order of 11 to 14 mm per year, considerably below the recorded historical average of 40 to 50 mm per year. Although the period of system operation and observed reduction in ground movement coincided with a period of below average precipitation, the observed natural background groundwater levels, particularly during spring freshet, were not significantly less than in previous years when average or above average ground movements were observed. The recently observed lower rate of movement is inferred to be due to the early effects of the subsurface dewatering system.

Although the 2012 subsurface dewatering system appears to be working, it is still early in the implementation stages and the full effectiveness of the system, particularly over longer periods of average or above average total precipitation, remains to be seen. The instrumentation system has also indicated that groundwater pressures and ground stability are also sensitive to the effects of surficial water infiltration, particularly that from intermittent storm events, surface runoff and water utility leaks. Key recommendations include:

1. Continue to operate, maintain and monitor the effectiveness of the subsurface dewatering system, and consider potential enhancements to the system on an annual basis.

2. Consider enhancement of the subsurface drainage system via additional pumping wells in the northwest corner of the landslide area and additional horizontal drain installations along the eastern toe of the landslide, generally north from Abbott Drive to Healy Street.

3. Proceed with full scale surface dewatering (Phase 3, after Dr. N Morgenstern's review of 2005), consisting of a comprehensive program of surface drainage improvement and water management which includes expansion and completion of the storm drain system in West Quesnel.

Further and more detailed conclusions and recommendations are provided in the report.

TABLE OF CONTENTS

Page #

1.0 INTRODUCTION 1

2.0 BACKGROUND 1

3.0 SUBSURFACE DEWATERING SYSTEM DESIGN 2

4.0 SYSTEM INSTALLATION 3
4.1 PUMPING WELLS 3
4.1.1 Drilling and Well Installation 3
4.1.2 Well Development and Short Term Pumping Test 4
4.1.3 Permeability and Transmissivity Analysis 5
4.1.4 Service Connections 6
4.1.5 Instrumentation 6
4.1.6 Dynamic Pump Controls 7
4.1.7 Optimization of the Pumping Well System 7
4.2 HORIZONTAL DRAINS 9
4.2.1 Drilling 9
4.2.2 Survey 10
4.2.3 Service Tie-in 11
4.2.4 Instrumentation 11
4.3 GROUNDWATER MONITORING WELLS (PIEZOMETERS) 12
4.4 IN-PLACE SLOPE INCLINOMETERS 13
4.5 DATA LOGGER STATIONS 14

5.0 DATA COLLECTION AND ANALYSIS 16
5.1 PUMPING WELLS 17
5.2 HORIZONTAL DRAINS 19
5.3 WATER QUALITY 21
5.4 GROUNDWATER (PIEZOMETRIC) PRESSURE 22
5.5 GROUND MOVEMENT - GPS HUBS 29
5.6 GROUND MOVEMENT - IN-PLACE SLOPE INCLINOMETERS 30
5.7 PRECIPITATION 31

6.0 SUBSURFACE DEWATERING SYSTEM EFFECTIVENESS 32
6.1 GROUNDWATER REMOVAL 32
6.2 GROUND MOVEMENT 38

7.0 CONCLUSIONS 42

8.0 RECOMMENDATIONS 43

9.0 CLOSURE 45

10.0 REFERENCES 46

TABLE OF CONTENTS

Page #

TABLES

Table 4.1 Pumping Well Installation Dates ... 3
Table 4.2 Short Term Pumping Tests ... 5
Table 4.3 Transmissivity and Hydraulic Conductivity ... 6
Table 4.4 Horizontal Drain Installation Dates ... 9
Table 4.5 Data Logger Station Power Connections ... 14
Table 5.1 Pumping Wells – Total Cumulative Annual Flow ... 18
Table 5.2 Horizontal Drains - Total Cumulative Annual Flow ... 19
Table 5.3 Individual HD Flow Readings (May 2013) ... 20
Table 5.4 2012 Borehole VWP Installations ... 22
Table 5.5 Background Piezometers – Overall Trend and Recent Observations ... 23
Table 5.6 Piezometers Near Pumping Wells – Overall Trend and Recent Observations ... 25
Table 5.7 Piezometers Near Horizontal Drains – Overall Trend and Recent Observations ... 28
Table 5.8 Typical Horizontal Movement (from GPS Hub 98-17) ... 29
Table 5.9 IPSI Horizontal Ground Movement ... 30
Table 5.10 Annual Total Precipitation (Quesnel Airport) ... 31

CHARTS

Chart 1 Unaffected groundwater levels, with regular seasonal (freshet) variation ... 34
Chart 2 Pumping Well (PW4, PW6, PW13) effects (starting November 2007 & March 2013) ... 34
Chart 3 Pumping Well (PW1) drawdown effect (starting October 2007) ... 35
Chart 4 Pumping Well (PW11) drawdown effect (starting spring 2013) ... 35
Chart 5 Groundwater decline at VWP3 corresponding with installation of HD11 (Aug 2012) ... 36
Chart 6 Inferred Horizontal Drain lowering of groundwater pressures (south of Abbott Drive) ... 36
Chart 7 Inferred Horizontal Drain lowering of groundwater pressures (north of Abbott Drive) ... 37
Chart 8 Typical movement (GPS 98-17) on an annual (Nov-Nov) basis (*only to July 2014) ... 38
Chart 9 Correlation between annual movement (GPS 98-17) and antecedent precipitation ... 39
Chart 10 Relation between background groundwater pressure and ground movement ... 41

FIGURES

Figure 1 Conceptual Subsurface Dewatering System
Figure 2 2012 As-Built Site Plan
Figure 3 Instrumentation Data Logger Site Plan
Figure 4 Overall Instrumentation Site Plan
Figure 5A Data Logger Connection Schematic (Station 01 through 10)
Figure 5B Data Logger Connection Schematic (Station 11 through 20)
Figure 5C Data Logger Connection Schematic (Station 21 through 30)
Figure 6 Incremental GPS Movement Vector Plan
Figure 7 Simplified GPS & IPSI Movement Vector Plan
Figure 8 Pumping Well & Horizontal Drain Productivity
Figure 9 Groundwater Drawdown
Figure 10 Daily IPSI Movement & Precipitation

TABLE OF CONTENTS

APPENDICES (Volume 2)

Appendix A	Photos
Appendix B	Logs (Wells, Horizontal Drains, Monitoring Wells, Slope Inclinometers)
Appendix C	Well Pump Tests
Appendix D	Installation Schematics
Appendix E	Pumping Well Flow and Level Data
Appendix F	Horizontal Drain Flow Data
Appendix G	Water Quality Data
Appendix H	Groundwater (Piezometer) Level Data
Appendix I	GPS Movement Data
Appendix J	Slope Inclinometer Movement Data
Appendix K	Weather Data

1.0 INTRODUCTION

In 2012, AMEC Environment & Infrastructure, a division of AMEC Americas Limited (AMEC) was authorized by the City of Quesnel to proceed with the implementation of a full scale subsurface dewatering system as part of the ongoing West Quesnel Land Stability Program. The purpose of the 2012 subsurface dewatering system was to reduce groundwater pressure in the upper fluvial sedimentary soils and in the lower Tertiary sediments in a previously identified landslide affecting a developed residential area. The main physical elements of the subsurface dewatering system which has been commissioned includes:

- 13 new vertical pumping wells (29 to 72 m deep);
- 10 sets of new horizontal drains (64 drains totaling 10,863 m);
- water level and flow metering controls;
- 14 groundwater monitoring wells fitted with 32 vibrating wire piezometers (VWP);two in-place slope inclinometers (IPSI);
- an instrumentation data logging network; and
- supporting utility services (power and water drainage).

The performance of the dewatering system was observed by monitoring of:

- flows from the pumping wells and horizontal drains;
- groundwater and pumping well levels with the VWPs;
- ground movement rates with the IPSIs and pre-established Global Positioning System (GPS) survey hubs; and
- precipitation via Environment Canada records for Quesnel Airport.

The 2012 system was designed to complement previously installed works that comprised four trial pumping wells, two trial horizontal drain installations, nine standpipe piezometers, 56 VWPs, 15 manually read slope inclinometers and 46 GPS ground movement survey hubs. This report contains a description of the installed system, presents the results of the monitoring data collected and provides a summary analysis of the system's performance observed to date in respect to reducing groundwater pressures and related ground movements.

2.0 BACKGROUND

Prior to implementing the 2012 subsurface dewatering system, extensive geotechnical investigation and monitoring was conducted in the West Quesnel area. In addition, during the 2012 and 2013 dewatering system installation and commissioning period, ongoing monitoring and reporting was carried out. To place the information presented herein in context with the available geotechnical background information and project history, this report should be read in conjunction with AMEC's previous report "*West Quesnel Land Stability Study*", dated May 2007[1]. Other relevant reports, including those summarizing annual monitoring results are listed under Section 10.0 References of this report.

The subsurface dewatering system described herein corresponds to the "Phase 2" depressurization program outlined by Dr. Morgenstern in his 11 October 2005 review of the proposed West Quesnel Land Stability Program on behalf of Emergency Management BC.

---

[1] AMEC Earth & Environmental, May 2007. West Quesnel Land Stability Study (2 Volumes).

3.0 SUBSURFACE DEWATERING SYSTEM DESIGN

The concept and recommended design for the subsurface dewatering system was proposed in AMEC's West Quesnel Land Stability Program report entitled, "*Trial Dewatering*", dated May 2008[2]. The design focused on using vertical pumping wells located to intercept groundwater mainly across accessible upper elevation portions of the landslide area and horizontal (i.e. gravity fed) perforated pipe drains within the toe of the landslide, to lower groundwater pressures within the slide mass. The proposed design consisted of 14 new pumping well sites and ten new horizontal drain installation sites, to complement the four pre-existing trial pumping wells and two pre-existing trial horizontal drain sites. Due to terrain and property access constraints, the specific locations of these components were modified somewhat during the installation process. The locations of the originally proposed dewatering system arrangement and the actual as-built installation are illustrated on Figures 1 and 2 respectively.

The completed pumping wells were fitted with level controls and water level recording devices and flow meters. The flowing horizontal drain installations were also fitted with flow meters. To monitor the effectiveness of the dewatering system, additional monitoring sensors for groundwater pressure and ground movement measurement were installed. The additional monitoring installations consisted of 32 VWPs and two IPSIs. The VWPs were installed within 14 boreholes, and placed in the general vicinity of the pumping well and horizontal drain locations to assist with assessment of the dewatering system effectiveness. The IPSIs were installed in locations of well documented movement along a well defined slip surface at the base of the landslide, to enable real-time monitoring of ground movements at depth. To efficiently and continuously collect monitoring data, all previously installed active and newly installed instruments were connected to data logger stations equipped with wireless modems for remote access. The locations of the data logger stations are depicted on Figure 3. The locations of all the various geotechnical monitoring instruments and components of the dewatering system are shown on Figure 4. The GPS movement hub locations are shown on Figures 6 and 7.

[2] AMEC Earth & Environmental, May 2008. Trial Dewatering West Quesnel Land Stability Program.

4.0 SYSTEM INSTALLATION

This section discusses the various aspects of the installed dewatering and monitoring system. Photos taken during the system installation are presented in Appendix A.

4.1 PUMPING WELLS

Table 4.1, below, provides a summary of the key dates associated with the pumping well installation and commissioning.

Table 4.1 Pumping Well Installation Dates

Pumping Well	Location	Drill Date	Pumping Test Date	Pump Installation Date	Full Start-up Date[1]
PW6	Lewis Dr.	May 8, 2012	Jun 15, 2012	Oct 17, 2012	Apr 1, 2013
PW7	Dixon St.	May 4, 2012	Jun 12, 2012	Oct 16, 2012	Apr 1, 2013
PW8	Dixon St.	May 3, 2012	Jun 11, 2012	Oct 16, 2012	Apr 1, 2013
PW9	South of Dixon St.	May 9, 2012	Jun 14, 2012	Oct 11, 2012	Apr 1, 2013
PW10	South of Dixon St.	May 9, 2012	NA	NA	NA
PW11	South of Abbot Dr.	May 11, 2012	Jun 15, 2012	Oct 12, 2012	Apr 1, 2013
PW12	Uplands Park	May 3, 2012	Jun 15, 2012	Oct 14, 2012	Apr 1, 2013
PW13	Paley Ave.	May 1, 2012	Jun 13, 2012	Oct 14, 2012	Dec 5, 2012
PW14	Dawson St.	May 8, 2012	Jun 13, 2012	Oct 14, 2012	Apr 1, 2013
PW15	South of Abbot Dr.	May 10, 2012	Jun 16, 2012	Oct 15, 2012	Nov 29, 2012
PW16	South of Abbot Dr.	May 11, 2012	Jun 14, 2012	Oct 13, 2012	Apr 1, 2013
PW17	South of Abbot Dr.	May 10, 2012	Jun 12, 2012	Oct 13, 2012	May 10, 2013[2]
PW18	Stork Ave.	May 6, 2012	Jun 16, 2012	Oct 15, 2012	Apr 1, 2013
PW19	Crane Ave.	May 7, 2012	Jun 11, 2012	Oct 15, 2012	Apr 1, 2013

Notes: 1. Date when pumps were generally considered to be operational on full time basis (intermittent shutdowns required to accommodate water quality sampling, optimization of pumping wells and maintenance).
2. Originally operational on April 1, 2013 but was shut off for cleaning and restarted on May 10, 2013.

4.1.1 Drilling and Well Installation

A total of 14 new pumping wells were drilled between the period of April 30 and May 11, 2012. The well drilling was completed by JR Drilling of Kamloops, BC using a Foremost DR-12 truck-mounted dual air rotary drill rig. The drilling process was monitored by AMEC, and the subsurface stratigraphy encountered was logged approximately based on the drill cuttings observed. The drilling utilizing a 250 mm (10 inch) diameter casing to an approximate depth of 6 m, and a 150 mm (6 inch) diameter casing to termination depth. Drill depths ranged from 16.8 m to 72.5 m depending on location. The associated drill logs are presented in Appendix B.

To maximize the effective depth of the wells, 114 mm (4.5 inch) diameter PVC screen was utilized for the full depth of drilling, with relatively short solid PVC sections near surface to allow for a surficial seal. To protect the wells a 150 mm (6 inch) diameter 5.5 m long steel casing was installed at surface around the PVC well pipe, with an exposed casing (stick-up) varying between 0.44 m to 0.76 m above ground surface depending on location.

A surface seal utilizing bentonite chips was established between the casing and the PVC well pipe to an approximate depth of 6.1 m below surface. No backfill material was utilized around the well screens.

Photos 1 though 6 and photo 16 in Appendix A illustrate some of the pumping well installation and connection operations.

4.1.2 Well Development and Short Term Pumping Test

Well development (short term pumping / surging / cleaning) was performed by Ingram Well and Pump Services (IWPS) to reduce the potential for sediment buildup in the wells, increase the permeability of the screened formations and to maximize the life expectancy of the pumps. Discharge water produced during well development was collected and disposed by IWPS off site, where required. With the exception of PW10, an acid treatment process was applied to all of the dewatering wells to increase permeability (by removing or inhibiting mineral incrustation). PW10 was determined to be dry at the completion of the drilling process and was left unmonitored and undeveloped.

Shortly after the development of the wells, short term pumping tests were conducted by IWPS as directed by AMEC to assess hydrogeological properties of the respective formations in order to optimize pumping ranges. IWPS installed a temporary 1/2 HP Grundfos VFD (variable speed drive) sampling pump into each well, except for PW6 and 13 where a 1 HP pump was used. The discharged water from pumping wells PW6, 7, 8, 12, 13, 14, 18, and 19 located within the residential community was directed to the closest sanitary sewer system manhole. Discharge from pumping wells on undeveloped rights-of-way at the locations of PW9, 11, 15, 16, and 17 was directed approximately 20 m down gradient along the right-of-way from each well.

In order to monitor water levels within the pumping wells during the short term pumping tests (pumping and recovery cycles), temporary pressure transducer equipped data loggers were used to record temperatures and water pressures which could be equated to water levels. AMEC suspended Solinst non-vented Leveloggers® to below the saturated zone in each of the pumping wells during test pumping and recovery periods. A Barologger® dedicated to recording atmospheric pressures was also utilized at each pumping well location in order to correct for atmospheric effects during the pumping tests. The data loggers were programmed to record pressure and temperature data at 1 minute intervals.

Each pumping well was manually monitored for a period of 6 hours while the remaining time was recorded by the data loggers. During each individual pumping test, the monitoring wells were drawn down to within approximately 5 m of the pump intake and then allowed to recover for the remaining allotted 6 hour manual monitoring period. The exceptions were PW6 and PW 13, which were pumped for 5 hours in order to draw down the wells, and then allowed to recover for 1 hour.

The short term pumping test curves for each well are presented in Appendix C. A summary of flow rates, pumping duration, recovery duration, total drawdown and total volume of water discharged is presented in Table 4.2, below.

Table 4.2 Short Term Pumping Tests

Pumping Well	Pump Rate (L/min)	Length of Pumping (min)	Recovery Time (min)	Initial Static Water Level Prior to Pumping Test (mbg)	Recovery Water Level After Pumping (mbg)	Total Drawdown (m)	Pumped Volume (L)
PW6	113.55	300	2217	6.39	9.39	14.47	33530
PW7	3.79	70	2574	3.69	4.68	21.00	261
PW8	4.54	153	1038	5.14	5.71	18.80	684
PW9	3.79	100	1080	8.52	8.76	19.10	373
PW10	-	-	-	-	-	-	-
PW11	3.79	76	1493	1.81	5.16	20.95	283
PW12	11.17	84	1248	4.64	5.06	59.54	923
PW13	37.85	300	815	14.60	14.72	5.13	11177
PW14	3.79	45	1281	0.90	2.21	10.70	168
PW15	3.79	90	1045	4.72	4.67	19.32	335
PW16	3.79	47	2754	13.11	19.18	11.69	175
PW17	3.79	96	2800	1.98	3.33	23.00	358
PW18	3.79	86	1278	2.39	2.42	30.58	320
PW19	5.68	70	2398	3.95	7.14	24.40	391

4.1.3 Permeability and Transmissivity Analysis

Short term pumping tests results were analyzed using the Cooper-Jacob time-distance drawdown method to determine transmissivity and permeability of the formation surrounding each pumping well. Aquifer transmissivity estimated using the Cooper-Jacob approximation of the modified non-equilibrium formula (Driscoll F.G., Groundwater and Wells, 1986) is shown below:

$$T = \frac{0.183Q}{\Delta s}$$

T is the aquifer transmissivity (m^2/day), **Q** is the pumping rate (m^3/day), and **Δs** is determined graphically as the drawdown (m) over one log cycle from a straight-line projection of the drawdown curve on the semi-logarithmic graph. Only one of these straight line segments is representative of the aquifer and that segment only is valid for analysis. The late recovery curve was determined as most representative as the aquifer response.

Storativity of the aquifer is estimated based on the distance and drawdown curve in monitoring wells. Due to site availability and time constraints, monitoring wells around each pumping well were installed after the short term pumping tests. Thus, no storage parameters were evaluated at this time.

Transmissivity and permeability results from the short term pumping tests are listed below in Table 4.3, below

Table 4.3 Transmissivity and Hydraulic Conductivity

Pumping Well	Transmissivity -T (m^2/s)	Hydraulic Conductivity - K (m/s)
PW6	1.197	5.4E-07
PW7	0.003	1.1E-09
PW8	0.048	1.9E-08
PW9	0.012	4.5E-09
PW10	-	-
PW11	0.004	1.4E-09
PW12	0.008	1.6E-09
PW13	3.323	6.9E-07
PW14	0.020	8.1E-09
PW15	0.017	6.7E-09
PW16	0.001	5.6E-10
PW17	0.002	1.0E-09
PW18	0.003	8.6E-10
PW19	0.006	1.6E-09

Transmissivity and permeability values from the formations encountered at PW6 indicated high flow capacities which is indicative of the sand and gravel units that were observed from 21 to 25 m below ground. High transmissivity and permeability values from PW13 appeared to reflect storage effects from the sand and gravel seams noted in the drill logs. The transmissivity and permeability values calculated for the other pumping wells were generally consistent with the range of values anticipated in fine-textured low permeability materials, which matches the stratigraphic observations made in the other monitoring wells.

4.1.4 Service Connections

To accommodate discharge flow from the new pumping well installations, Canadian Western Mechanical (CWM) installed various new storm and sanitary systems as designed by Urban Systems Ltd (Urban). A pitless adaptor component (Mass Midwest) buried approximately 3 m below surface was utilized to make the connection between each pumping well and its associated drainage system. To reduce the influx of well flow into the sanitary system, all newly installed pumping wells (except PW13 & PW19) were connected to the storm system. Urban's as-built drawings/reporting should be referred to for additional details with regard to the installed drainage system.

Surveyed locations of the pumping wells were provided by McElhanney Consulting Services Ltd. (McElhanney).

4.1.5 Instrumentation

After the wells were developed and connected to the City infrastructure the pumps were installed by IPWS. The wells were equipped with conventional water level loggers to control the pumping cycles, and a cycle sensor to protect the pump from cavitations and dry run and to prolong the time expectancy of the pumps. The wells were also fitted with vibrating wire piezometers (VWP) and flow meters to measure water levels and flow volumes.

To optimize the size and type of the pump utilized in each well, the short term pumping test data was utilized. In all developed wells (except in PW6 and PW13), 19 L/min (5 gpm), ½ HP pumps were utilized with a 3.79 L/min (2 gpm) restrictor. PW6 originally utilized a 114 L/min (30 gpm), 1 HP pump) however this was subsequently changed out and replaced with a 19 L/min (5 gpm), ¾ HP pump with a variable drive pump control. PW13 utilizes a 57 L/min (15 gpm), 1 HP pump with a 38 L/min (10 gpm) restrictor. In addition PW13 has a gate valve fitted at the outlet into the sanitary system that further restricts the flow to approximately 27 L/min.

Similar to the four wells previously installed during the previous trial dewatering program, all the new pumping wells were equipped with conventional static level logger controls and cycle sensors. The level loggers were installed such that the upper limit (pump 'on' level) was approximately half way between the originally observed static water elevation and the bottom of the well. The lower limit (pump off level) was set directly above the pump intake. The cycle sensor monitors the current output of the pump and is set to stop the pump if the current is less than 95% of normal output. These static level loggers in conjunction with the cycle sensors that protect the pump allow for conventional static control of the pumps.

To monitor the water drawdown effect, a VWP string was placed inside a 25 mm (1 inch) solid PVC pipe within each well, with the VWP tip placed roughly 0.8 m above the top of the pump. To monitor the flow (well production levels) a Seametrics IP81 paddle wheel flow meter was installed in all wells. The flow meter was placed above the restrictor, if present, and below the pitless adaptor. Additional information associated with the installed pumps, VWP's and flow meters is presented on the pumping well schematics found in Appendix D.

4.1.6 Dynamic Pump Controls

To enable optimization and remote control of the pumping wells, AMEC installed a dynamic control system for all the new and previously installed pumping wells. The dynamic controls utilize the VWP data in conjunction with the data loggers and electrical relays to enable remote control of the pumping well limits and optimization of the pumping cycles. However, due to the complexity of the controls, the static pump levels were also maintained as backup. For all previously installed pumping wells a switch was installed to select the control type. For all newly installed pumping wells the control type is selected by an electronic relay switch. The electrical and data connections were performed by James and Sons Electric Ltd. with AMEC's direction and assistance.

Currently, all pumping wells except PW5 and PW6 utilize dynamic controls. PW5 requires a new VWP, while PW6 requires a new subpanel connection as the variable drive controller is potentially outside the manufacturer's recommended wiring distance, and thus has limited to no communication capabilities with the pump. AMEC utilizes these dynamic controls on a regular basis to monitor and adjust the pumping cycles as necessary with changing conditions.

4.1.7 Optimization of the Pumping Well System

Over the years, starting from the original trial dewatering program various pumping well maintenance issues and optimization opportunities have been encountered. The major optimization that was done to the pumping wells was the implementation of the dynamic pump controls as described in Section 4.1.6, above. Below is a summary of other significant issues/optimizations performed.

Trial pumping well PW2 was originally installed in September 2007, and in May 2009 failed. While it was operational, the well had only a slight drawdown effect on the surrounding groundwater levels and extracted a minimal volume of water. Thus, when the pump failed, due to the low impact to the system and budget constraints it was left unrepaired. As part of the 2012 dewatering system installation, PW2 was proposed to be re-established. During the replacement process the draw pipe broke and the original pump fell to the bottom of the well. The pump was deemed non-retrievable and was left at the bottom of the well. The well was than cleaned (acid-washed) and a new pump was installed 3 m above the original pump location at 33.5 m below surface.

Trial pumping well PW4 historically had been classified as the highest producer prior to the 2012 dewatering system installation. However, unlike all the other pump wells installed as part of the trial dewatering program this pump utilized only the cycle sensor to control the pumping cycles. The installed level loggers were not able to accommodate the rapid draw down and recharge of this well, and over time had failed. To enable optimization of this pumping well, dynamic pump controls and a valve at the outlet of the pump were installed to reduce the flow and increase the drawdown and pump cycle time.

PW6 was originally fitted with a 1 HP pump and variable pump controls; however, this pump continued to have reoccurring issues that to date have not been fully resolved. From the short term pumping test it was determined that this well would likely be a high producer, thus to accommodate a large anticipated flow, the original 114 L/min (30 gpm) 1 HP pump was installed. The pump was able to draw down the water in the well within the first few days; however, over time the pump was proven to be oversized for the formation. The variable pump controls that are designed to lower the production level could not lower the pump's production to the required flow level. Thus, on 5 June 2014 the pump was replaced by a 19 L/min (5 gpm), ¾ HP pump. During replacement and removal of the pump it was also deemed necessary to clean the well due to sediment build up. After the replacement of the pump was completed, it was noted that the variable pump controller had malfunctioned and it was replaced by a new controller. This was the third pump controller utilized for this well, and similarly to the failed controller, communication between the pump and the new controller was not able to be established. Currently the pump is controlled only by the cycle sensor, and no remote control of this pump is possible.

Shortly after the initialization of the pumping in PW13, an issue similar to that at PW4 was experienced. A rapid drawdown followed by a rapid recharge was observed. To solve this issue, an additional flow regulator in a form of a gate valve was installed at the outflow of the pumping well into the sewer system that restricts the outflow to approximately 27 L/min.

Although the new system wells were originally drilled in May 2012 with the development of the wells completed in June 2012, the pumps were not able to be placed in the wells until October 2012 pending the completion of various utility connections. Furthermore, due to environmental constraints related to water disposal, the pumps in the wells connected to the storm system remained idle until 1 April, 2013. Due to the inactivity in the wells, sediment build-up within the wells was observed. As the wells became operational, some of the sediment dissipated over time and the pumps were able to operate unhindered. PW17 however was not able to function properly due to higher sediment build-up in the well. In May 2013, PW17 was acid washed (developed) once again, and was also suspended at a slightly higher elevation (depth of 26.2 m as opposed to original pump depth of 28.3 m).

As part of the environmental constraints, the quality of pump discharge water entering the storm system was to be tested on a regular basis by Urban/City representatives. In order to accomplish the required water sampling, AMEC manually and remotely turned off the pumps the night before the testing date to ensure that water from each well could be collected when the field water sampling staff were in position. It is believed that this interruption in the automated pumping cycle in addition to potentially shallow burial depth of the outflow pipe resulted in the freezing of PW18 in the winter months. To protect the PW18 pump, the pumping well was turned off on January 29, 2014 and then restarted on May 8, 2014. Deeper burial and/or other forms of frost protection are being considered for future operation of this well.

4.2 HORIZONTAL DRAINS

A total of ten horizontal drain sites (HD5 through HD14) were developed between July 19 and Sept 27, 2012. Two of the horizontal drain sites (HD9 and HD12) coincided with the locations of two previous trial dewatering drain sites (HD1 and HD4 respectively). Photos 19 thorough 36 in Appendix A illustrate various aspects of the horizontal drain installation and connection process.

Table 4.4 below, presents key dates associated with the horizontal drain installation. Figure 4 depicts the locations of all the horizontal drain sites and plan view of the individualized drain fans in relation the installed instrumentation. Appendix B presents the individualized drain plan and profile views, with an inferred stratigraphy based on observations of drill cutting returns. The length along each drain where natural formation water return was first suspected was noted where possible, and used to approximately infer the section along each drain where groundwater may be entering.

Table 4.4 Horizontal Drain Installation Dates

Drain Site	General Location	Drill Date(s)	Start of Automated Flow Data Collection	Number of Drains	Total Drain Length (m)	Median Drain Length (m)
HD5	South of Healy St.	Aug 21-23, 2012	NA	4	1006	252
HD6	South of Healy St.	Aug 24, 2012	NA	3	754	251
HD7	East of Pentland Cres.	Aug 27, 2012	NA	3	118	47
HD8	West of Lewis Dr.	Sep 11-22, 2012	Nov 11, 2012	11	1512	137
HD9	West of Lewis Dr.	Aug 28-Sep 1, 2012	Nov 16, 2012	10	1073	88
HD10	West of Bouchie St.	Sep 17-19, 2012	Nov 29, 2012	7	948	134
HD11	South of Abbot Dr.	Jul 27-Aug 8, 2012	Jun 12, 2013[1]	6	1349	197
HD12	West of Adam St.	Jul 19-23, 2012	Oct 10, 2012	9	1708	197
HD13	South end of Adam St.	Aug 15-18, 2012	Nov 15, 2012	6	1344	248
HD14	South of Healy St.	Sep 7-8, 2012	NA	5	1050	154

Note: 1. Flow meter was installed on HD11 on Oct 19, 2012 gave inaccurate readings until corrected on Jun 12, 2013.

4.2.1 Drilling

The horizontal drilling and drain installation was completed by Jensen Drilling of Eugene Oregon, USA utilizing a purpose-built track-mounted horizontal mud rotary drill. The drilling was monitored by an AMEC representative and the characteristics of the soils penetrated were approximately inferred when possible/available via drill cutting return. The drains were arranged in a fan like pattern at each of the drain site locations.

To accommodate the horizontal drill and the drilling process at each site, the City of Quesnel prepared access, comprised of a working platform typically 15 m long by 15 m wide, a near vertical drill face approximately 1.5 m in height and 12 m wide, and a temporary sump near the vertical drill face.

A total of 10,863 m of drain pipe was installed in 64 individual drain holes. The drains were drilled at various azimuths and with starting inclinations between -5° and +2°. Individual plan and profile views for each of the installed drains along with inferred stratigraphy are presented in Appendix B.

A typical drain installation consisted of a solid 37.5 mm (1.5 inch) diameter PVC drain pipe extending into the drill face to a maximum length of 6.1 m. A slotted 37.5 mm diameter PVC pipe was attached to the end of the solid PVC pipe and extended to the drilled length. To seal the opening at the drill face, bentonite chips were utilized as a surface plug extending a maximum 1.0 m into the ground. No other backfill material in around the slotted or solid PVC drain sections was utilized.

During the drilling process, return water management was handled by the City of Quesnel. The drilling for the HD8 drains encountered higher groundwater flows than anticipated, such that the temporary sump that was prepared was not sufficient to handle the water volume. To accommodate the excess flow, the City of Quesnel excavated a temporary ditch along an adjacent fence line and routed the water across Lewis Drive through a series of temporary culverts. In addition, due to the volume of water expelled at this location it was difficult to form a bentonite surface seal around the installed drains. To accommodate the surface seals, 'fillcrete' (low strength 1 to 2 MPa concrete) was used as backfill in around the drain outlets and their connecting manifold. To assist with the surface seals, the last two drains (HD8-10 and HD8-11) installed at this site were cased wish a 102 mm (4 inch) diameter steel casing with a rubberized bushing set between the casing and the drain pipes. During the drilling and installation of the horizontal drains at this location, significant lowering of the upper Lewis Pond was observed, such that the pond was considered to have dried up.

The drilling at HD9 and HD10 also resulted in larger than anticipated water flows. At HD9, a trench was dug and outflow was temporarily routed to a nearby sewer system. At HD10 a sump pump was utilized to route the water into the nearby sewer system. To accommodate surface seals, 3.1 m long by 102 mm diameter steel casing sections with rubberized bushings set between the casing and the drain pipes were also utilized at HD10.

4.2.2 Survey

To assess the approximate underground position of the installed horizontal drains, AMEC utilized a Reflex EZ-AQ down-hole surveying tool. The surveying of the horizontal drains was done between 7 August 2012 and 11 October 2012 (Photos 25 though 30, Appendix A). The tool was inserted into each completed drain and an orientation measurement was taken at 3 m intervals until the end of the drain was reached or a blockage in the drain prevented further advancement. With post processing of the data collected during the survey, drain profiles were established relative to the starting locations. Utilizing the collar location, and initial azimuth surveyed by McElhanney, the relative drain profiles were depicted in UTM coordinates. Appendix B presents profiles and plan views of each of the drains.

4.2.3 Service Tie-in

The locations and requirements for pipe manifolds, service connections, electrical and data conduits for each horizontal drain site were designed by Urban.

When the drilling, installation and the profile drain surveys were completed, CWM constructed a plumbing manifold system to interconnect all the drain pipes at each horizontal drain site. The manifolds were then connected to a dedicated manhole. To enable future cleaning, if/when required, cleanout ports for each drain and manifold were also installed. The cleanouts for the drains were buried (a metallic cap is placed at the end of each drain), while the manifold cleanouts have an exposed cover. In addition to the cleanouts, each drain was installed with a service connection shutoff valve that allows isolation and measuring of flows from individual drains. To protect the manifolds from freezing during the winter, native material that was excavated during the site preparation was used as backfill cover (except in HD8 where fillcrete material was used) in around the installations. As the backfill alone would not provide sufficient frost protection for the manifolds and their exposed drain outlets in the manholes, heat tape was placed around the exposed pipes and rigid foam insulation was used to encapsulate the entire horizontal drain installation.

At HD5, HD6, HD7, and HD14 no significant or measurable flow was noted after the drains were installed. Thus, at these locations the temporary sump was backfilled, the drill face was left unaltered, and not connected to any drainage system.

At HD8, HD9, and HD13 the outflow from the dedicated manholes was tied into the nearby storm drainage system. At HD10 the outflow from the dedicated manhole was connected into the nearby sanitary sewer system. At HD11 the outflow from the dedicated manhole was directly connected into Abbott Pond. At HD12 the outflow from the dedicated manhole was connected into the existing HD4 manhole which in-turn was previously connected to the City sewer as part of the trial dewatering program. In addition to the water drainage connections, CWM installed electrical and data conduits, utilizing the trenches required for the drain pipe connections where possible. AMEC, with the assistance of James and Son’s Electric utilized the installed electrical and data conduits to connect power and data lines between the dedicated horizontal drain manholes and the associated instrument data logging and control stations.

Some post construction backfill settlement occurred, such that some shutoff valves and drain cleanouts protrude from the finished grade. In addition, it was noted that some of the shutoff valves at HD9 have been destroyed subsequent to installation.

4.2.4 Instrumentation

Shortly after the installation of the horizontal drains, manual flow readings were initiated on the individual drains. The manual readings were collected on a daily basis when AMEC representatives were present on site and as frequently as possible until automated flow meters were installed (as per Table 4.4). Magnetic-type flow meters (magmeters) were installed at the horizontal drain installations to continuously monitor the flows. Magmeters have no moving parts and thus should have a lower probability of getting clogged or frozen, however they require electrical power connections between the data monitoring stations and the dedicated manholes at each horizontal drain site.

Due to low and non-measurable flows observed shortly after the drilling and installation process no flow meters were installed at HD5, HD6, HD7, and HD14.

Initially at HD8 a 50.8 mm (2 inch) diameter magmeter was utilized. This flow meter has the ability to measure flows ranging between 22.7-1136 L/min. In the spring of 2013, it was noted that the water level in the manifold cleanout was rising and could potentially overflow and flood a nearby residence. The water rising in the cleanout is due to the flow meter backing up the system. To prevent the overflow, an additional 76 mm (3 inch) diameter magmeter was installed in June 2013. The additional magmeter has the ability to measure flows ranging between 53.0-2536 L/min. The installed flow meters were installed in a parallel system, and can be isolated if necessary. Currently both installed magmeters are utilized to measure the outflow at HD8.

The initial flow meters installed at HD9, HD10, HD11, HD12 and HD13 were low flow 19 mm (¾ inch) magmeters that have the ability to measure flows between 0.8 and 75.7 L/min. In the fall of 2013, it was noted that the measured flows at HD11 and HD13 reduced to below the detection limit of those magmeters. To enable lower flow measurements, secondary low flow 10 mm (3/8 inch) magmeters connected in parallel were installed. These new flow meters have the ability to measure flows between 0.1 and 11.4 L/min. The 19 mm magmeters are utilized during anticipated periods of higher flows (spring/summer), while the 10 mm magmeters are utilized during expected low flow periods (fall/winter). Isolation valves are located in the dedicated manhole, which can be uses to switch between the magmeters as required.

The magmeter at HD11 was initially not providing accurate flow readings due to electrical supply issues, thus between October 2012 and June 2013, false flow readings were recorded. On 12 June 2013 an electrical sub-panel was installed within the dedicated manhole to rectify the problem. The false flow readings recorded at this station were ignored and thus gap in the data set during that time period exists.

Connection schematics for the horizontal drain installations are presented in Appendix D.

4.3 GROUNDWATER MONITORING WELLS (PIEZOMETERS)

A total of 14 new monitoring wells (see Photos 7 though 12 in Appendix A) were completed between the period of August 1 and August 24, 2012. The installation locations were selected for up gradient proximity to the new/existing dewatering infrastructure (pumping wells and horizontal drains) to aid in assessment of the impact of the dewatering system on groundwater pressures in the slide mass. Each new monitoring well was completed with a nest of two or three electronic vibrating wire piezometers (VWPs), i.e. electronic sensors capable of measuring groundwater pressures acting at the point of installation in the ground. A total of 32 new VWPs were installed. Typically the bottom VWP in a well was placed at an elevation approximately where the lower slide failure surface or a water bearing soil layer (typically a sand or gravel seam) was suspected. The upper VWPs were placed relatively equidistant between the bottom VWP and the ground surface, preferably in a coarse grained soil layer (sand or gravel), if present. In four of the wells an additional third VWP was installed for greater coverage or to target an additional potential zone of interest. The VWP instruments were manufactured by Geokon (supplied by GKM Consultants). The rated pressure capacity of these VWP’s ranged from 350 to 1000 kPa and the installed depth ranged from 12.2 to 67.1 m below ground surface.

The holes for the groundwater monitoring locations were drilled by Boart Longyear (Boart), subcontracted by Mud Bay Drilling Co. Ltd., utilizing a SR-160 track-mounted sonic drill rig.

During the drilling process, care was taken to collect and dispose of the drill cuttings, particularly when the located directly within the residential area. AMEC field personnel monitored the drilling process, collected continuous sonic core samples and field logged the encountered stratigraphy. The collected core samples were then transported to AMEC's Prince George laboratory where more detailed core logging was performed. The associated logs and photos of the retrieved core samples are presented in Appendix B.

The VWP's were installed within the drilled borehole utilizing a fully-grouted installation technique. To precisely achieve and confirm the installation depth of each VWP, the sensors were connected to a 25 mm (1 inch) PVC tubing at a specific target depth by the drilling crew under the direction of AMEC field personnel. The PVC tubing was then lowered down the borehole and utilized as a bottom up grouting tube, displacing the water within the borehole.

Flush mount casing protectors were installed at surface to protect the installed VWP wiring. A conduit between the flush mount casing protector and the associated data logging instrumentation station was installed by CWM. Connecting data cables were installed by AMEC with the assistance of James and Son's Electric (see Photos 13 though 18, Appendix A). Upon completion of monitoring wells, McElhanney surveyed the locations of the flush mount casing protectors.

The installation schematics for the groundwater monitoring wells are presented in Appendix D.

4.4 IN-PLACE SLOPE INCLINOMETERS

Two in-place slope inclinometer (IPSI) strings were installed inside conventional slope inclinometer pipe casings. These two new installations were designated SI16 and SI17. Drilling for installation of the SI16 casing was done by JR Drilling using a Foremost DR-12 truck-mounted dual air rotary drill rig. SI17 was drilled by Boart Longyear's SR-160 track-mounted sonic drill rig. AMEC representatives monitored the drilling process and logged the subsurface conditions encountered. In addition to standard field logging, the sonic core retrieved from SI17 was logged in more detail at AMEC's Prince George laboratory. Conventional slope inclinometer casing, consisting of grooved 75 mm and 85 mm diameter PVC pipe was installed in SI16 and SI17 respectively. A fully grouted installation technique with a bottom casing anchor and grout valve was utilized at both locations. Upon completion of IPSI installations, McElhanney surveyed their locations. Photos 37 though 42 in Appendix A depict the drilling and instrumentation installation process. The borehole logs for the IPSI installations are presented in Appendix B.

Prior to placement of the IPSI strings, a conventional manual slope inclinometer survey was performed at each location to establish an initial reference baseline for possible future manual surveys. To enable real-time monitoring of ground movement, two IPSI strings (each consisting of six 1 m fixed length slope inclinometer sensor segments) were suspended in the slotted casings at SI16 and SI17 on 20 September 2012 and 16 October 2012 respectively. The sensor strings were suspended from approximately 46 to 52 m (SI16) and 61 to 67 m (SI17) below ground surface, depths judged to likely span across the anticipated location of the landslide failure surface. Break-away points were established for each IPSI string in order to allow for possible retrieval and re-deployment of a portion of the installed sensor strings should sufficient casing deflection and/or shear result in the sensor string becoming jammed in the hole.

Both IPSI locations have above ground pre-cast concrete manhole installations placed directly over the slope inclinometer casing installations. At SI16 the manhole also contains the instrument's data logger station, while at SI17 the manhole is used only as a junction point for the data cables, with an underground conduit routing the cables from the instrument to its associated data logger station.

The installation schematics for the IPSI strings are presented in Appendix D.

4.5 DATA LOGGER STATIONS

In order to collect and transmit real-time electronic instrument data, 11 new data logging stations (STN) were installed, adding to 17 pre-existing stations for a total of 28. The formerly designated STN01 and STN05 instrumentation locations do not have any associated real time or electronic instruments and were not further developed with active data loggers. With the exception of, STN14 and STN15, all the other completed data logger stations are permanently connected to the BC Hydro electrical grid. Table 4.5, below provides a summary of the power connection status of each station site.

Table 4.5 Data Logger Station Power Connections

Station #	Power Drop	Year Connected	Station #	Power Drop	Year Connected
STN01[1]	None	N/A	STN16	Overhead	2008
STN02	Overhead	2008	STN17	Overhead	2008
STN03	Overhead	2012	STN18	Overhead	2008
STN04	Underground	2012	STN19	Overhead	2008
STN05*	None	N/A	STN20	Overhead	2012
STN06	Overhead	2008	STN21	Overhead	2012
STN07	Overhead	2012	STN22	Overhead	2012
STN08	Overhead	2012	STN23	Overhead	2012
STN09	Overhead	2012	STN24	Overhead	2012
STN10	Underground	2012	STN25	Overhead	2012
STN11	Overhead	2012	STN26	Overhead	2012
STN12	Overhead	2012	STN27	Overhead	2012
STN13	Overhead	2012	STN28	Overhead	2012
STN14	Battery	N/A	STN29	Underground	2012
STN15	Battery	N/A	STN30	Underground	2012

Note: 1. Non-active station

At each active station a data logger and associated components are typically housed inside a fibreglass instrument box which was in turn mounted inside a custom aluminum cabinet in order to provide a secure and weather resistant housing. The exception is STN03 at the Voyageur School, where the fibreglass instrument box was placed inside a pre-cast concrete manhole ring installation fitted with a locking steel cover. This manhole installation was also directly placed above the SI16 location. For all other stations, the aluminum cabinets were attached to metal base plates that are founded on concrete manhole rings.

All final station locations were surveyed with a handheld GPS and are illustrated on Figures 2 through 4.

The various wires for all instruments and power connections associated with a station are routed through conduits and are attached to the data loggers and control systems as required. A series of connection schematics depicting the instrumentation connection layout for the network of data logger stations are presented on Figures 5A 5B, and 5C. Each data logger station was custom assembled by AMEC personnel, and was then connected and powered as required with the assistance of James and Sons Electric. A typical data logger installation consists of a data logger, power inverter with a battery backup power supply, and a cellular modem. Additional peripherals are also attached to the data logger as needed, based on the instrumentation type(s) being monitored by the station. Photos 43 through 48 depict the various components of the field data collection and logging stations.

Data loggers, peripherals, inverters, batteries and cellular modems were supplied by Campbell Scientific. The data loggers are capable of storing data received by the flow meters, VWP's and IPSI systems. The cellular modems were connected to the Bell network and are utilized on a daily basis or when required. Through this system, one is able to retrieve data, modify instrument settings, optimize pumping cycles, and troubleshoot the system remotely. A proprietary AMEC web-based interface and database is utilized to automatically retrieve, store, post correct/process the data and provide data graphs as required.

5.0 DATA COLLECTION AND ANALYSIS

Overall, the West Quesnel subsurface dewatering and monitoring system comprises 18 vertical drilled pumping well installations of which 17 are operational, have been connected and are actively monitored for water levels and flow volumes. There are also 12 drilled horizontal drain installation sites (comprising 68 individual drains) of which seven sites have been connected and are actively monitored for flow volumes. Groundwater levels are monitored by 84 vibrating wire piezometers of which eight have been damaged, are not currently giving reliable measurements and/or their location has gone dry. A total of 17 slope inclinometer installations have been completed over the years to measure subsurface ground movements, of which two have been recently installed and equipped with real-time in-place sensors. The original 15 manually read slope inclinometer installations have long since either sheared off or were judged to be not deep enough to display useful information and are not currently monitored. Further ground surface movement information is available from an array of 46 functional GPS hubs that are manually surveyed on an approximately quarterly basis.

As the instrumentation sites are dispersed over a wide area in West Quesnel, a supporting network of 28 electronic data logger stations is utilized. These stations are also equipped with cellular modems that allows for wireless and remote transmittal of the collected data.

To help manage the frequency and volume of instrumentation data, AMEC has implemented a custom internal computer database and web-based interface to retrieve, store, filter, plot and analyse the data. The database is currently configured to connect to the data loggers on a daily basis (except for STN's 14 and 15) and update the database during the night (updates typically are done between 2 am to 8 am, PST) allowing for near real-time data review remotely. STN's 14 and 15 currently utilize only battery power, and thus to conserve energy the cellular modems only activate on Monday, Wednesday, and Friday around 10 am and the data associated with these stations are updated the following night.

5.1 PUMPING WELLS

To monitor pumping well performance, each well is equipped with a flow meter (manufactured by Seametrics, supplied by Jadler Industries Ltd.) and a vibrating wire piezometer (manufactured by Geokon and supplied by GKM Consultants) connected to a data logger that collects raw data. The raw data from the flow meters is in a form of ‘counts’. These counts represent a number of revolutions made by the meter’s paddle-wheel in a known and calibrated (K value) fitting. The collected raw count data is then transmitted to the database where the instrument’s designated K value is used to calculate water flow rates. Currently, hourly count readings are recorded by the data logger for all pumping wells.

The raw data collected by the data logger from the vibrating wire piezometer inside each well is in a form of frequency and temperature. The frequency reading is generated by the vibration of the sensor at a specific depth and confining pressure. The temperature reading is the measured temperature of the sensor tip. The collected raw data is then transmitted to the database where a polynomial data reduction utilizing VWP specific calibration values is used to compute the groundwater (piezometric) pressure acting on the sensor tip at the installation depth, utilizing a temperature and barometric pressure correction. The measured groundwater pressure acting at the installation depth is used to calculate the height (and elevation) of an equivalent column of groundwater acting on the instrument. Occasionally this automated electronic data measurement and collection process produces an erratic spike in the raw data and a false reading (noise) is recorded (particularly for older versions of the instruments). To eliminate the erratic spikes for display purposes, the raw collected data is electronically filtered utilizing anticipated data ranges and typically observed rates of change. These filters are dynamic and are monitored and adjusted on a regular basis to ensure that only erratic readings related to background noise are filtered and actual reliable data points are maintained. Currently hourly VWP readings are recorded by the data logger for all pumping wells.

For maintenance and troubleshooting, AMEC is able to connect to the data loggers directly and enable a separate data collection file, to review the collected data on a minute by minute basis. If needed there is also the ability to observe raw data on a 20 second real time basis to further troubleshoot the system, but this frequency of real time data cannot be collected due to the limitations of the data logger and associated internal data logger program.

To enable the control of the pumping cycles AMEC can connect to the data logger directly and override the automated control for all the pumping wells, except for PW5 and PW6 (See Section 4.1.6 for further detail).

A table providing the pumping well details along with plots of well levels and flow rates observed since installation can be found in Appendix E. These plots were generated by AMEC’s custom database management system. Longer term plots for a five year period between August 1 2009 and July 31, 2014 are presented where data is available. Other reporting intervals are available. Well water levels presented on all the plots found in Appendix E are averaged daily values with digital filtering to remove erroneous readings. Table 5.1 presents the measured cumulative discharge flows from pumping wells on an annual basis.

Table 5.1 Pumping Wells – Total Cumulative Annual Flow

Pumping Well	Total Cumulative Flow Per Year (L)							
	2008	2009	2010	2011	2012	2013	2014[2]	Total
PW1	35,182	34,044	30,349	27,738	26,867	25,968	15,080	195,228
PW2	9,063	3,655[1]	Pump Failed			2,668[1]	2,459	15,386
PW4	6,261,725	5,233,493	4,663,930	6,145,276	3,810,749	3,052,650	1,653,934	30,821,757
PW5	644	711	615	1,134	1,613	2,685	1,303	8,705
PW6					35,940	2,766,654	1,023,313	3,825,907
PW7					321	66,372	45,906	112,599
PW8					682	347,589	357,026	705,297
PW9					949	621,910	1,021,788	1,644,647
PW10						Dry/not used or monitored		
PW11					560	80,110	56,982	137,652
PW12					300	502,858	335,671	838,829
PW13					288,641	7,592,947	3,534,328	11,415,916
PW14					641	119,548	93,038	213,227
PW15					859	244,830	165,422	411,111
PW16					532	16,222	10,027	26,781
PW17					530	90,417	74,522	165,469
PW18					1,123	391,458	163,255	555,836
PW19					8,177	98,713	82,164	189,054
Total	**6,306,614**	**5,271,903**	**4,694,894**	**6,174,148**	**4,178,484**	**16,023,599**	**8,636,218**	**51,283,401**

Notes: 1. PW2 data from 2009 represents values collected prior to the pump failing in May 2009. Data for 2013 represents values collected after the pump was replaced in May 2013.
2. Data for 2014 is from January 1, 2014 to July 31, 2014 only.

5.2 HORIZONTAL DRAINS

Following an initial period of manual measurements, a series of automated flow meter instruments were brought on line to monitor the horizontal drain production. The flow meters (magmeter, manufactured by Seametrics, supplied by Jadler Industries Ltd.) were installed on the drain manifold discharges at all monitored horizontal drain site locations. These are connected to data loggers that only collect raw electronic data.

The raw data is in the form of 'counts'. The magmeter utilizes an electromagnetic induction principal to measure the flow of water passing through a calibrated opening. For the flow readings to be accurately recorded the flow through the calibrated opening needs to be void of air gaps (i.e. must be a full pipe). To ensure this requirement is observed the flow meters were installed with an upward flow gradient through the calibrated opening. Similar to the paddle-wheel flow meters, collected raw data is then transmitted to the database, were the counts are converted utilizing the instrument's K value into flow data. Currently, hourly count readings are recorded by the data logger for all the horizontal drain flow meters.

Similarly to the pumping wells, horizontal drain flow data can be reviewed by on a minute basis through direct connection with the data logger, and even on a 20 second real-time basis, if needed, to troubleshoot and to review flow patterns.

Appendix F contains a table further describing the details of each particular horizontal drains, followed by plots of the recorded flow data (average daily rates) for each horizontal drain site up to July 31, 2014. Table 5.2, presents a summary of measured discharge flows on an annual basis.

Table 5.2 Horizontal Drains - Total Cumulative Annual Flow

Drain Site	Total Cumulative Flow Per Year (L)							
	2008	2009	2010	2011	2012	2013	2014[5]	Total
HD1	Dry, Decommissioned							
HD4	1,046,984[1]	536,559	421,820	432,021	448,443[2]	535,725	296,554	3,718,106
HD5					Dry/not monitored			
HD6					Dry/not monitored			
HD7					Dry/not monitored			
HD8					60,390,352	130,934,967	60,821,772	252,147,091
HD9					2,772,172	4,134,390	3,478,452	10,385,014
HD10					8,682,037	8,326,985	6,088,651	23,097,673
HD11					267,408[3]	6,291,139	2,068,722	8,627,269
HD12					3,151,386	3,210,809	2,327,408	8,689,603
HD13					1,254,748	1,914,268[4]	2,672,151	5,841,167
HD14					Dry	2,015,064	Dry	2,015,064
Total	**1,046,984**	**536,559**	**421,820**	**432,021**	**76,966,546**	**157,363,347**	**77,753,710**	**314,520,987**

Notes: 1. HD4 flows for 2008 were interpolated based manual flow readings.
2. HD4 plugged due to nearby drilling, and no flow readings were observed between August to mid November 2012.
3. HD11 flows for 2012 are only manual readings taken during and shortly after installation, as the originally installed flow meter malfunctioned; this was corrected mid 2013, no trends yet established to allow interpolation of the lost flow readings during this period.
4. HD13 flows dropped below the detectable limit of the flow meter in mid September 2013. In mid November 2013 a secondary flow meter was installed with a lower detection limit to continue recording the lower flow. Zero flow was recorded between mid September to mid November 2013.
5. Data for 2014 is from January 1, 2014 to July 31, 2014 only.

Although no initial measurable water flow was noted at HD14, one drain (HD14-2) began to produce water during the 2013 spring freshet, and the flow rate was periodically manually measured by the City of Quesnel and AMEC, until it stopped flowing in mid-summer 2013. No significant or measurable flow was observed for this or any other apparently dry horizontal drain sites. The observed flow at HD14-2 might be attributed to a water main leak that was detected and fixed by the City in around the same time period and in the general location of the associated drain.

In order to assess the flow from individual drains within some of the horizontal drain installation sites, on May 7 and 8, 2013 AMEC conducted a field flow switching and measurement program. The installed shut-off valves were utilized to sequentially isolate individual pipes and the manifold magmeter was used to measure the flow from the isolated pipe. The flow rates were measured on a per minute basis, for a minimum of 10 minutes and averaged over a day. Table 5.3, below presents the calculated daily average flows for the individual drains. Please note that due to the relatively short data collection period the values below are approximate and only represent the flows at the time they were taken. Flows rates under different conditions and time of the year will vary.

Table 5.3 Individual HD Flow Readings (May 2013)

Drain Site	Daily Average Flow Rate (L/day)										
	Drain1	Drain2	Drain3	Drain4	Drain5	Drain6	Drain7	Drain8	Drain9	Drain10	Drain11	Total
HD4	1,527	578	NA	NA	NA	NA	NA	NA	NA	NA	NA	2,105
HD8	8,640	66,240	NA	164,160		47,520	87,840	4,320	NA	76,320	21,600	476,640
HD9	Flow readings unable to be assessed											23,504
HD10	0	18,582	21,517	648	432	0	216	NA	NA	NA	NA	41,394
HD11	Flow readings unable to be assessed											NA
HD12	1,233	0	7,627	0	0	0	601	0	0	NA	NA	9,461
HD13	3,024	648	3,576	864	0	1,841	NA	NA	NA	NA	NA	9,954
HD14	0	21,600	0	0	0	NA	NA	NA	NA	NA	NA	21,600

During individual drain isolation for the HD8 drains, excessive seepage around the shut-off drains was noted. To avoid potential unintended water diversion and damage to the surficial seals for the drains, individual flow rate measurements at drains HD8-3 and HD8-9 were not completed. At HD9 it was noted that some of the shut-off valves were damaged and thus an accurate assessment of the individual drain flows could not be conducted. At HD11, large fluctuations in flow were observed and the installed flow meter was determined to be malfunctioning so an individual flow measurement for each drain was not completed.

Of note, during review of collected flow data and while manually measuring horizontal drain flows, AMEC observed a phenomenon in which the flow pattern appears to rhythmically surge on a short term basis. Further investigation and analysis is required to try and understand this phenomenon.

5.3 WATER QUALITY

Water quality samples were collected by AMEC from each pumping well shortly after the completion of the short term pumping tests, with the exception of the dry well (PW10). Water quality samples were also collected from HD8 through to HD13 on the 10th of September and 18th of October 2012. It was not possible to take water quality samples from HD5, 6, 7 and 14 due to lack of measurable and collectable flow. The samples were submitted to ALS Environmental (ALS) in Vancouver, B.C. for testing. The test results are presented in Appendix G, and have been provided to Urban Systems Ltd. for further environmental analysis.

Regular water quality sampling of pumping well water and horizontal drain water collected by the City of Quesnel staff and as directed by Urban Systems Ltd. continued throughout 2013 and 2014. AMEC remotely assisted the water quality sampling procedure, by cycling pumps as required. Further details with regard to the water quality testing are reported by Urban Systems Ltd. in their draft report: "*Environmental Impact Study – Groundwater Release to Baker Creek*" dated September 2014.

5.4 GROUNDWATER (PIEZOMETRIC) PRESSURE

To monitor changes in the groundwater pressures and assess the effectiveness of the dewatering system, additional vibrating wire piezometers (VWP) were installed in some of the new boreholes completed during 2012. Summary information regarding the new piezometers is provided in Table 5.4 below. Note that within this report and appendices, reference to specific vibrating wire piezometers uses the convention of "VWP#L", where # denotes the number of the borehole where the instrument was installed (eg 26 for BH26) and L denotes the letter (A, B, or C) corresponding to the placement depth within the borehole.

Table 5.4 2012 Borehole VWP Installations

Borehole	Maximum Pressure Capacity (kPa)			Installed Depth (m)			Monitoring Target
	A	B	C	A	B	C	
BH26	350	700	-	13.7	29.3	-	PW6, 7
BH27	350	700	-	13.9	30.9	-	PW7, 8
BH28	350	350	-	14.0	27.3	-	PW9
BH29	350	350	-	14.0	22.6	-	PW11
BH30	350	350	-	13.4	22.3	-	PW11, 15
BH31	350	350	-	14.2	22.3	-	PW15, 16
BH32	350	350	-	14.0	22.3	-	PW16, 17
BH33	350	700	1000	13.7	22.9	64.3	PW13
BH34	350	350	700	11.3	23.5	39.0	PW18
BH35	350	350	700	13.7	27.4	48.8	background
BH36	350	700	1000	18.3	41.1	67.1	HD7, 8
BH37	350	700	-	12.2	34.1	-	HD10
BH38	350	700	-	13.7	34.4	-	PW19, HD12
BH39	350	700	-	14.2	19.8	-	background

More detailed information regarding the 2012 and all the other previously installed piezometers is provided in Appendix H.

Similar to the VWP's used in the pumping wells, the raw data collected by the data logger from the groundwater level VWP's is in the form of frequency and temperature, which is then transmitted to the database where a conversion to calculated height (and elevation) of an equivalent column of groundwater acting on the instrument takes place. Currently VWP readings are recorded either hourly or every six hours depending on the specific data logger and other instruments attached to it.

Appendix H contains a series of plots depicting the groundwater pressures measured by the instrumentation system. The average daily groundwater pressure (given as an equivalent total head elevation) is presented in the plots. Depending on the location of the VWP's, they depict various short and long term groundwater conditions within the West Quesnel area. Some near surface installations are more sensitive to seasonal precipitation trends, short term weather events and potential water service line breaks, particularly if they are installed in shallow sands or gravels. Deeper installations tend to show longer term background trends with subdued seasonal response indicative of larger scale, more regional groundwater conditions. Some of the piezometers show the effects of nearby dewatering installations (pumping wells and horizontal drains).

Table 5.5 Background Piezometers, below (also reproduced as Table H1 in Appendix H), presents the individual trends and observations for piezometer locations that are judged unlikely to have been affected by the dewatering efforts to date, and are more reflective of general background subsurface groundwater patterns in West Quesnel. Note that some VWP's that fell into this category in previous annual reporting have been affected by the dewatering infrastructure installed in 2012 and have therefore been moved to other appropriate categories.

Table 5.5 Background Piezometers – Overall Trend and Recent Observations

Instrument	Background Groundwater Condition	Post Dewatering Observations	Difference Between Pre and Post Dewatering
VWP 4	Steady-state at 521 m elevation until sharp rise to 526 m elevation in April 2009, spike to 531.8 during BH 35 installation during summer of 2012	Steady-state near 527 m with slight seasonal groundwater response	Relatively unchanged
VWP 7A	Varies, 537 m to 537.5 m elevation	Slight seasonal groundwater rise to 537.5 m in spring, then decreased to 537 m	Relatively unchanged
VWP 7B	Varies, 535 m to 536 m elevation	Steady-state near 535 m with slight seasonal groundwater response	Relatively unchanged
VWP 8A	Steady-state at 513 m elevation, intermittently dry	Dry	Unchanged
VWP 8B	Steady-state at 513 m elevation, intermittently dry	Dry	Unchanged
VWP 8C	Steady-state at 511 m elevation	Steady-state near 510.5 m	0.5 m decrease
VWP 8D	Gradual decline from 508 m to 505 m elevation, with slight seasonal precipitation response	No seasonal response, continued gradual decline to 504 m	1 m decrease
VWP 11A	Steady-state at 517 m elevation	No significant change, possibly dry	Unchanged
VWP 11B	Steady-state at 515.4 m elevation with slight seasonal precipitation response	Steady state near 515.2 m with slight seasonal precipitation response	Relatively unchanged
VWP 11C	Slight decline 515 m to 514 m elevation	Steady state near 514 m with slight seasonal precipitation response	Relatively unchanged
VWP 13A	Varies, generally between 480 m to 479 m elevation, slight longer term decline	Seasonal groundwater responses, varied between 480 m and 479 m	Relatively unchanged
VWP 13B	Varies, generally between 481 m to 482.5 m elevation	Seasonal groundwater responses, varied between 481 m and 482.5 m	Relatively unchanged

Table 5.5 Background Piezometers – Overall Trend and Recent Observations, Continued

Instrument	Background Groundwater Condition	Post Dewatering Observations	Difference Between Pre and Post Dewatering
VWP 14A	Varies, 566 m to 568 m elevation, with seasonal precipitation response	Seasonal groundwater responses, varied between 566 and 567 m	Relatively unchanged
VWP 14B	Varies, 530 m to 531 m elevation, with minimal seasonal precipitation response	Steady state near 530 m	Relatively unchanged
VWP 14C	Varies, 529 m to 530 m elevation, with minimal seasonal precipitation response	Steady state near 529 m	Relatively unchanged
VWP 15A	Varies, 560 m to 563 m elevation, with strong seasonal and storm precipitation response	Seasonal groundwater response in the spring, from 560 m to 563 m. Dissipated to 560.5 m	Relatively unchanged
VWP 15B	Gradual decline from 540 m to 537.5 m elevation	Gradual decrease to 537 m	0.5 m decease
VWP 15C	Gradual decline from 538 m to 534.5 m elevation	Gradual decrease to 533.5 m	1 m decrease
VWP 16A	Gradual rise from 645 m to steady-state near 646.5 m elevation	Steady state near 646.5 m	Relatively unchanged
VWP 16B	Increasing from 580 to 589 m elevation until August 2010, steady state until May 2012, then decreasing to near 587 m	Steady state near 587 m	Relatively unchanged
VWP 16C	Steady-state near 550 m elevation	Steady state near 550 m	Relatively unchanged
VWP 16D	Slight variation, near 550 m elevation	Steady state near 550 m	Relatively unchanged
VWP 35A	Varies, 531 m to 532.5 m elevation, with seasonal precipitation response	Seasonal groundwater response in the spring, from 531.5 m to 532.5 m	Relatively unchanged
VWP 35B	Varies, 530 m to 531 m elevation, with seasonal precipitation response	Seasonal groundwater response in the spring, from 530 m to 531 m	Relatively unchanged
VWP 35C	Gradual decrease from 532 m to near 528.5 m elevation	Steady state near 528.5 m	3.5 m decrease
VWP 39A	Varies, 564 m to 561.5 m elevation, intermittently dry, seasonal precipitation response	Seasonal groundwater responses, varied between 561.5 m and 564 m, intermittently dry	Relatively unchanged
VWP 39B	Varies, 561 m to 558 m elevation, with seasonal precipitation response	Seasonal groundwater responses, varied between 558 m and 561 m	Relatively unchanged

Table 5.6, Piezometers Near Pumping Wells, below (Table H2 in Appendix H), presents overall trends and observations for piezometers that are situated near the pumping wells and may have been influenced by them. The piezometers nearest the pumping wells and closer to surface have experienced the greatest influence (reduction in groundwater pressure) since pumping started and many have reached a new steady-state level, depending on how productive the well has been. Piezometers that have groundwater pressures exhibiting steady-state levels (with or without seasonal influences) are considered to be out of the radius of influence of the wells or are too deep to be influenced. Some of the piezometers influenced by the pumping wells are also still reactive to seasonal precipitation.

Table 5.6 Piezometers Near Pumping Wells – Overall Trend and Recent Observations

Instrument	Background Groundwater Condition	Post Dewatering Observations	Difference Between Pre and Post Dewatering
VWP 3 (PW2)	Groundwater level generally varied between 500 to 501 m elevation with seasonal precipitation response; level began to decrease from near 500.5 m following horizontal drain installation in 2012	Continued decrease, to near 495.5 m	5 m decrease
VWP 3A (PW1)	Decreased from start of pump trials in Nov. 2007 until mid-2009, from 518.5 to 504.5 m elevation	Steady state near 504.5 m	14 m decrease
VWP 3B (PW1)	Decreasing from start of pump trials in Nov. 2007, from 518.5 to 505.5 m elevation	Steady state near 505.5 m	13 m decrease
VWP 4A (PW1)	Steady-state near 516 m elevation with spikes due to precipitation events, no apparent influence from pumping	No significant change	Relatively unchanged
VWP 4B (PW1)	Steady-state near 516 m elevation with spikes due to precipitation events, no apparent influence from pumping	No significant change	Relatively unchanged
VWP 9A (PW12)	Varies, 529.5 m to 530.5 m elevation, with seasonal precipitation response	Seasonal groundwater rise to 530 m in the spring, then gradual decrease to near 529 m	Relatively unchanged
VWP 9B (PW12)	Varies, 530 m to 531 m elevation, with slight seasonal precipitation response	Decreased from near 531 m to near 529 m, following activation of PW12 in April 2013. Seasonal groundwater rise to 530 m	1 m decrease
VWP 9C (PW12)	Varies, 531.5 to 529 m elevation	Decreased from near 531 m to near 529 m, following activation of PW12 in April 2013	2 m decrease
VWP 10A (PW14)	Varies, 541 m to 542.5 m elevation, with seasonal precipitation response	Decreased from near 542 m to near 540 m, following activation of PW14 in April 2013 Seasonal groundwater rise to 543 m	2 m decrease
VWP 10B (PW14)	Varies, 541 m to 543 m elevation, with seasonal precipitation response	Decreased from near 542 m to near 532.5 m, following activation of PW14 in April 2013	9.5 m decrease
VWP 10C (PW14)	At or near 536 m elevation, slightly decreasing over time	Decreased from near 536 m to near 531 m, following activation of PW14 in April 2013	5 m decrease
VWP 12A (PW4)	Decreased from start of pump trials in Oct. 2007 until early 2008 from 545 to near 538 m elevation, dry	Dry	7 m decrease

Table 5.6 Piezometers Near Pumping Wells – Overall Trend and Recent Observations, Continued

Instrument	Background Groundwater Condition	Post Dewatering Observations	Difference Between Pre and Post Dewatering
VWP 12B (PW4)	Decreased from start of pump trials in Oct. 2007 until early 2008, from 545 to 537 m elevation, steady state since then	Steady state near 537 m	8 m decrease
VWP 12C (PW4)	Decreased from start of pump trials in Oct. 2007 until early 2008, from 537 to below 530 m elevation. Intermittently dry	Seasonal groundwater response in the spring, from 530 m to 532.5 m	7 m decrease
VWP 12D (PW4)	Steady state near 526 m elevation, no apparent influence from pumping or seasonal precipitation response	Steady state near 526 m	Relatively unchanged
VWP 17A (PW5)	Gradual decrease from start of pump trials in Oct. 2007 until present, from 484 to 483 m elevation, with slight seasonal precipitation response	Continued decrease, to near 482.5 m	1.5 m decrease
VWP 17B (PW5)	Gradual decrease from start of pump trials in Oct. 2007 until present, from 483 to 482 m elevation, with slight seasonal precipitation response	Continued decrease, to near 480 m	3 m decrease
VWP 18A (PW5)	Gradual decrease from start of pump trials in Oct. 2007 until present from 481 to 479.5 m elevation	Steady state near 479.5 m	1.5 m decrease
VWP 18B (near PW5)	Not working	n/a	n/a
VWP 19A (PW4)	Decreased from start of pump trials in Oct. 2007 until early 2008, from 545 to 541 m elevation, possibly dry	Possibly dry	4 m decrease
VWP 19B (PW4)	Decreased from start of pump trials in Oct. 2007 until early 2008 from 545 to 538 m elevation	Steady state near 538 m	7 m decrease
VWP 20 (PW4)	Gradual decrease from start of pump trials in Oct. 2007 until early 2008, from 545 to 542 m elevation), seasonal increases to 543 m	No significant change, similar seasonal variation	3 m decrease
VWP 26A (PW6 and PW7)	Decreasing from 554 m to 552 m elevation since installation, slight seasonal precipitation response	Seasonal groundwater response in the late spring, from 552 m to 553 m. Dissipated to 551.5 m	0.5 m decrease
VWP 26B (PW6 and PW7)	Decreasing from near 555 m to near 553 m elevation since installation	Decrease from 553 m to 551.5 m	1.5 m decrease
VWP 27A (PW7 and PW8)	Decreasing from near 553 m to 552.5 m elevation since installation	Seasonal groundwater response in the late spring, from 552.5 m to 553 m	Relatively unchanged
VWP 27B (PW7 and PW8)	Steady state near 551.5 m elevation, no apparent influence from pumping	Steady state near 551.5 m	Relatively unchanged
VWP 28A (PW9)	Decreasing from near 551 m to 550.5 m elevation since installation	Seasonal groundwater response in the spring, 549 to 550.5 m	Possibly 0.5 m decrease

Table 5.6 Piezometers Near Pumping Wells – Overall Trend and Recent Observations, Continued

Instrument	Background Groundwater Condition	Post Dewatering Observations	Difference Between Pre and Post Dewatering
VWP 28B (PW9)	Decreasing from near 551 m to 550.5 m elevation since installation	Seasonal groundwater response in the spring, 549 to 550.5 m	Possibly 0.5 m decrease
VWP 29A (PW11)	Decreasing from near 555 m to near 551 m elevation since installation	Seasonal groundwater response in the spring, from 551 m to 552.5 m	Possibly 2.5 m decrease
VWP 29B (PW11)	Decreasing from near 556 m to near 551 m elevation since installation	Seasonal groundwater response in the spring, from 551 m to 552.5 m	Possibly 3.5 m decrease
VWP 30A (PW11 and PW15)	Decreasing from near 558 m to near 555 m elevation since installation	Seasonal groundwater response in the spring, from 555 m to 557.5 m	Possibly 1.5 m decrease
VWP 30B (PW11 and PW15)	Decreasing from near 558 m to near 554.5 m elevation since installation	Seasonal groundwater response in the spring, from 554.5 m to 557 m	Possibly 1.5 m decrease
VWP 31A (PW15 and PW16)	Decreasing from near 558.5 m to near 557.5 m elevation since installation	Seasonal groundwater response in the spring, from 557.5 m to 558.5 m	Relatively unchanged
VWP 31B (PW15 and PW16)	Decreasing from near 553 m to near 550.5 m elevation since installation	Seasonal groundwater response in the late spring, from 550.5 m to 551 m	Relatively unchanged
VWP 32A (PW16 and PW17)	Decreasing from near 560.5 m to near 559.5 m elevation since installation	Seasonal groundwater response in the spring, from 559.5 m to 561 m	Relatively unchanged
VWP 32B (PW16 and PW17)	Decreasing from near 560.5 m to near 559.5 m elevation since installation	Seasonal groundwater response in the spring, from 559.5 m to 560.5 m	Relatively unchanged
VWP 33A (PW13)	Dry	Dry	Unchanged
VWP 33B (PW13)	Decreasing from near 526.5 m to near 525.5 m elevation since installation	Decreasing from 525.5 m to near 522 m with activation of PW13 in Jan 2013	3.5 m decrease
VWP 33C (PW13)	Gradual decrease from near 530 m to near 519 m elevation since installation	Steady decrease from 519 m to near 514 m with activation of PW13 in Jan 2013	5 m decrease
VWP 34A (PW18)	Varies, between 511.5 m and 512 m elevation, with seasonal precipitation response	Seasonal groundwater response in the spring, from 512 m to 513 m	Relatively unchanged
VWP 34B (PW18)	Decreasing from near 513 m to near 511.5 m elevation since installation	Seasonal groundwater response in the spring, from 511.5 m to 512.5 m	Relatively unchanged
VWP 34C (PW18)	Varies, near 512 m elevation, with seasonal precipitation response	Seasonal groundwater response in the spring, from 512 m to 513 m	Relatively unchanged

Table 5.7 Piezometers Near Horizontal Drains, below (Table H3 in Appendix H), presents the overall trends and observations for piezometers situated above or near the horizontal drain installations. These piezometers have generally been at steady-state since initial declines in 2012 when the horizontal drains (HD) were first installed. A number of piezometers in the vicinity of HD8 show a continuing decreasing trend, and a couple of these instruments also display seasonal response.

Table 5.7 Piezometers Near Horizontal Drains – Overall Trend and Recent Observations

Instrument	Background Groundwater Condition	Post Dewatering Observations	Difference Between Pre and Post Dewatering
VWP 21A (HD4/HD12)	Varied, between 499 m and 501 m elevation, with significant seasonal precipitation response; until affected by HD12 install in summer of 2012 drawing down from 500 m to 498 m	Seasonal increase to 500 m, dissipated to 498 m	2 m decrease
VWP 21B (HD4/HD12)	Varied, between 500.5 m and 501.5 m elevation, with seasonal precipitation response, large drop to 492.5 m after HD12 install in summer of 2012	Seasonal increase to 493 m in the spring, dissipated to near 492.5 m	9 m decrease
VWP 22 (HD4/HD12)	Varied, 504.5 m to 505.5 m elevation, with seasonal precipitation response, large drop to 497.5 m after HD12 install in summer of 2012	Seasonal increase to 498 m in the spring	7 m decrease
VWP 23A (HD9)	Steady state near 495 m elevation, no apparent seasonal or influence from horizontal drains	Steady state near 495 m	Relatively unchanged
VWP 23B (HD9)	Gradual decrease since installation of trial HD1 in Nov. 2007 until mid-2010 from near 495 m to 489 m elevation, steady-state since then, no seasonal precipitation response	Slight seasonal fluctuation, near 489 m	6 m decrease
VWP 24 (HD9)	Decreased upon installation of trial HD1 in Nov. 2007 from 501 m to below 492 m elevation, dry	Dry	9 m decrease
VWP 25A (HD9)	Varies, 500 to 501 m elevation, very slight seasonal precipitation response, no apparent influence from horizontal drains	Steady state near 500 m	Relatively unchanged
VWP 25B (HD9)	Steady-state near 498 m elevation, no apparent seasonal or influence from horizontal drains	No significant change	Relatively unchanged
VWP 36A (HD8)	Dry	Dry	Unchanged
VWP 36B (HD8)	Near 502 m elevation shortly after installation	Gradual decrease from 502 m to near 495 m	7 m decrease
VWP 36C (HD8)	Near 501.5 m elevation shortly after installation	Gradual decrease from 501.5 m to near 492.5 m	9 m decrease
VWP 37A (HD10)	Dry	Dry	Unchanged
VWP 37B (HD10)	Decreasing from near 508 m shortly after installation	Gradual decrease to near 493 m	15 m decrease
VWP 38A (HD4/HD12)	Varied from near 494.5 m to 492 m elevation, with seasonal precipitation response	Seasonal increase to 494.5 m in the spring	Relatively unchanged
VWP 38B (HD4/HD12)	Near 500 m shortly after installation	Gradual decrease with seasonal variations between 489 and 492 m	11 m decrease

5.5 GROUND MOVEMENT - GPS HUBS

Monitoring of ground movement in West Quesnel is primarily carried out by comparing changes in the specific positions of defined surface reference points (hubs) over time, as measured periodically by Global Positioning System (GPS) survey (most recently conducted by McElhanney). No new GPS hubs where added as part of the 2012 subsurface dewatering system installation, and the previously established GPS hub network was utilized. The existing GPS hubs have been read approximately quarterly and are reported in AMEC's 2012[3] and 2013[4] Annual Monitoring Reports. The most recent quarterly GPS survey occurred in July 2014. Appendix I contains a complete summary of the various GPS surveys and related movement plots.

Table 5.8 presents some typical cumulative, annual, and peak movement rate data for a 'worst-case', but typical monitoring location in the middle of West Quesnel (GPS Hub 98-17), from 1998 to the latest reading in July 2014.

Table 5.8 Typical Horizontal Movement (from GPS Hub 98-17)

Year	Annual Movement (mm)	Cumulative Movement (mm)	Peak Movement Rate (mm/yr)[1]
1998	n/a[2]	16[2]	66
1999	80	96	115
2000	67	163	110
2001	62	225	75
2002	54	279	83
2003	21	300	23
2004	22	322	22
2005	87	409	75
2006	14	423	75
2007	24	447	43
2008	59	506	160
2009	68	574	216
2010	6	580	56
2011	8	588	107
2012	47	635	93
2013	12	647	38
2014	14[3]	661[3]	39

Notes: 1. Peak movement rate only, typically observed over short quarterly spring period.
2. Represents only part of annual movement, measured from September 1998.
3. Represents only part of annual movement, measured to July 2014.

Figures 6 and 7 attached to this report provide detailed and simplified plan views of the horizontal movement vectors for the array of GPS hubs in West Quesnel. Section 6.2 below, provides a detailed discussion regarding the more recently observed rates of ground movement in relation to the early apparent effects of the subsurface dewatering system.

[3] AMEC Earth & Environmental, February 2013. 2012 Annual Monitoring Report.
[4] AMEC Earth & Environmental, March 2014. 2013 Annual Monitoring Report.

5.6 GROUND MOVEMENT - IN-PLACE SLOPE INCLINOMETERS

In the fall of 2012, two real time electronic in-place slope inclinometer (IPSI) strings were installed across the approximate depths of previously detected landslide failure surfaces. The data loggers connected to the two new IPSIs record the relative inclination (tilt) of each of the six sensor segments (about 2 vertical axes designated A and B) in each string. The inclination data is then converted to an equivalent horizontal displacement for each sensor segment. By plotting and comparing changes for each sensor in the string over time, a depth to a shearing surface that crosses the string and the rate of horizontal movement on that surface can be estimated. By being fixed in-place, the instruments allow real-time monitoring of ground movement in a fairly precise manner. The data reduction is performed by the connected data logger; however raw data is also collected, transmitted and stored by AMEC's data management system. The system can also monitor and display the movement readings and transmit movement threshold warnings.

Data collection for the two IPSI installations SI16 and SI17, commenced 20 September 2012 and 16 October 2012 respectively. The data is currently gathered hourly. Plots of the average daily displacement in the primary (A) direction, the secondary direction (B) and the resultant direction (AB) direction for each IPSI installation are presented in Appendix J.

While with the conventional slope inclinometer and GPS surveys used in the past movement was detected and quantified, the quarterly measurement schedule did not allow determination of the exact time(s) and patterns of movement on other than a very approximate (typically 3 month) basis. Since installation, the IPSI instruments show that ground movement has occurred as several distinct, relatively small and isolated short term movement events or 'spikes'. Table 5.9 provides a summary of those detected movement events, as interpreted from the data plots provided in Appendix J. Section 6.2 below, provides more discussion regarding these observed rates of ground movement in relation to the early apparent effects of the subsurface dewatering system.

Table 5.9 IPSI Horizontal Ground Movement

Movement Event	SI16 Movement (mm)	SI17 Movement (mm)
September 20-22, 2012	1.5	n/a[1]
October 17-18, 2012	1.5	2
January 3-7, 2013	3	4
April 29 – May 7, 2013	5	6
December 19-22, 2013	2	3
April 20-24, 2014	2.5	3.5
May 26-31, 2014	2.5	3
June 6-11, 2014	1	1.5
Cumulative Movement	19	23

Note: 1. SI17 not yet installed at that time

5.7 PRECIPITATION

Site specific weather measurement and data collection was not part of the 2012 subsurface dewatering system implementation. The previously established meteorology station (by Urban) has not been in operation over this time period, and no new instruments were established. However, as part of AMEC's annual monitoring program for the West Quesnel Land Stability Program, precipitation records are retrieved from Environment Canada for the Quesnel Airport weather station located approximately 5.5 kilometers to the northeast of the study area. Reference plots of total precipitation are provided in Appendix K.

Table 5.10 below provides summary of annual total precipitation (snow and rainfall) going back to 1996. Generally during the drainage implementation period from 2012 through to present, the total precipitation averaged over each year has been approximately 78% of what is considered normal (taken as 536 mm per year), indicative of a slight drying trend. However that drying trend was not as significant as that observed 2009 and 2010, which was about 69% of the historical normal.

Table 5.10 Annual Total Precipitation (Quesnel Airport)

Year	Annual Total Precipitation (mm)	Difference from 1981-2007 Historical Normal (mm)
1996	657	+121
1997	579	+43
1998	488	-48
1999	628	+92
2000	554	+18
2001	554	+18
2002	471	-65
2003	478	-58
2004	692	+156
2005	524	-12
2006	465	-71
2007	541	+5
2008	530	-6
2009	423	-113
2010	315	-221
2011	450	-86
2012	427	-109
2013	404	-132
2014[1]	247[1]	n/a

Note: 1. Precipitation only for part year up to July 31, 2014

Further detail related to precipitation patterns during the implementation of the 2012 subsurface dewatering system is provided in AMEC's annual monitoring reports for 2012 and 2013.

6.0 SUBSURFACE DEWATERING SYSTEM EFFECTIVENESS

In general, historic groundwater levels within the West Quesnel area have been considered to be generally quite high and detrimental to slope stability. Previous studies have also demonstrated a clear correlation between periods of higher precipitation, increased water infiltration into the ground, subsequently higher groundwater pressures and increased landslide movement. Studies have also indicated that the most cost effective way to increase stability and reduce movement would be by implementing a comprehensive program of surface and subsurface drainage to control and reduce groundwater pressures. Theoretically an overall average reduction in groundwater pressure across West Quesnel by several meters acting on the landslide failure surface should result in and increased factor of safety and reduction of landslide related movements to manageable levels (AMEC September 2002, AMEC May 2007, AMEC May 2008). The 2012 subsurface dewatering program was intended as the first major component of an overall dewatering strategy for West Quesnel intended to control and reduce groundwater pressures (the second component consisting of surface drainage works and water management, also referred to as “Phase 3” by Morgenstern, 2005).

The 2012 subsurface dewatering system has only been fully operational for a relatively short time. The horizontal drains were installed gradually between July and September 2012. The pumping wells were not fully operational and online until April 2013. While the horizontal drains have been observed through two spring freshets, the entire system has only experienced one full season and freshet. Accordingly, the time frame of data collection for comparison to background conditions, including taking into effect the natural variation in weather patterns, is still quite limited and many observations and conclusions are preliminary. The following sections provide more detail regarding the apparent performance of the system and comparison against background groundwater conditions, precipitation patterns and observed ground movement between 2012 and July 2014.

6.1 GROUNDWATER REMOVAL

The pattern of groundwater removal and subsequent effects on groundwater pressures in West Quesnel are monitored in two ways. The first is by measurement of the volume of water extracted by the pumping wells and horizontal drains. The second is by long term observations of groundwater pressures in the various VWP instruments scattered across the area.

Section 5.1 and associated data and plots presented in Appendix E provide detail as to the water extracted by the pumping wells. As expected, there is a fair amount of variability in flow depending on the season and local geological formation permeability. Figure 8 provides a graphical depiction of the estimated productivity (daily average flows) of the various pumping wells since their installation and commissioning. What are considered to be very productive wells are those in the northwest quadrant of the landslide area, typically producing flows of water greater than 5,000 litres per day (PW4, PW6, PW13). The current best well, PW13, typically produces between 15,000 and 20,000 litres per day. These higher productivity wells appear to be drawing a considerable amount of water from surficial post glacial fluvial (sand and gravel) sediments that overlie and likely are a source of recharge of groundwater into the underlying slide mass. The five next most productive wells are scattered further to the south and to the east (PW8, PW9, PW12, PW15, PW18), extracting between 500 and 5000 litres of water per day, likely from more permeable water bearing seams, lenses and fissures within the underlying fine grained soils and Tertiary bedrock. The relatively poorly producing wells are considered the eight wells (PW1, PW2, PW7, PW11, PW14, PW16, PW17, PW18), that produce less than 500 litres per day. However even some of those poor volume producers have been able to show some effect on reducing adjacent groundwater pressures. PW9 was formerly considered a poor producer but has generally increased production over time, and others may as well. Also of note are PW1 and PW14, that although producing less than 500 liters per day of water on average, have been observed to produce noticeable reductions in the surrounding groundwater pressures (as depicted in charts presented below). One well originating from previous trial dewatering and permeability testing (PW5) in the eastern toe region of the landslide typically produces less than 10 litres per day of water and is not considered to be useful in dewatering. PW10 (not shown on Figure 8) was dry at the time of drilling, and was not completed as a pumping well.

Section 5.2 and Appendix F provide detailed information regarding the flows from the horizontal drain installations located along the lower and eastern toe of the landslide area. Again, there is a significant amount of variability both seasonally and with location. Figure 8 provides a graphical depiction of the estimated productivity (daily average flows) of the various horizontal drain sites since installation.

In most respects the horizontal drains exceeded expectations in terms of volumes of flow produced, even well after initial installation. All the drain sites south of Lewis Pond are very good producers, on average producing in excess of 5000 litres per day, and typically between 20,000 and 40,000 litres per day during spring freshet, far exceeding even the best pumping well. Horizontal drain installation HD8 has been even more successful, producing water at an order of magnitude greater than other horizontal drains, typically in the range of 200,000 to 300,000 litres per day, but peaking to as much as 600,000 liters per day during freshet. Disappointing though, was the general lack of measureable production from four horizontal drain sites (HD5, HD6, HD7, and HD14) in the northeast corner of the landslide. These installations did not encounter enough water bearing units or seams. It should be noted however that HD14 has intermittently produced some water, and that some of these apparently dry drains may still be useful at intercepting water in future years.

The VWP installations are the key instruments used to measure groundwater pressures in West Quesnel, and plots of their measurements over time can be used to detect the influence of the pumping wells and horizontal drains. Plots of groundwater pressures for all instruments are provided in Appendix H.

Chart 1, following, depicts an example of measured groundwater levels for several VWP's located in the upper western region of the landslide, an area that is considered to be beyond the likely influence of the wells and horizontal drains. The observed pattern can be considered typical of the natural, undisturbed or 'background' steady state groundwater conditions, showing some seasonal fluctuation corresponding to each spring freshet.

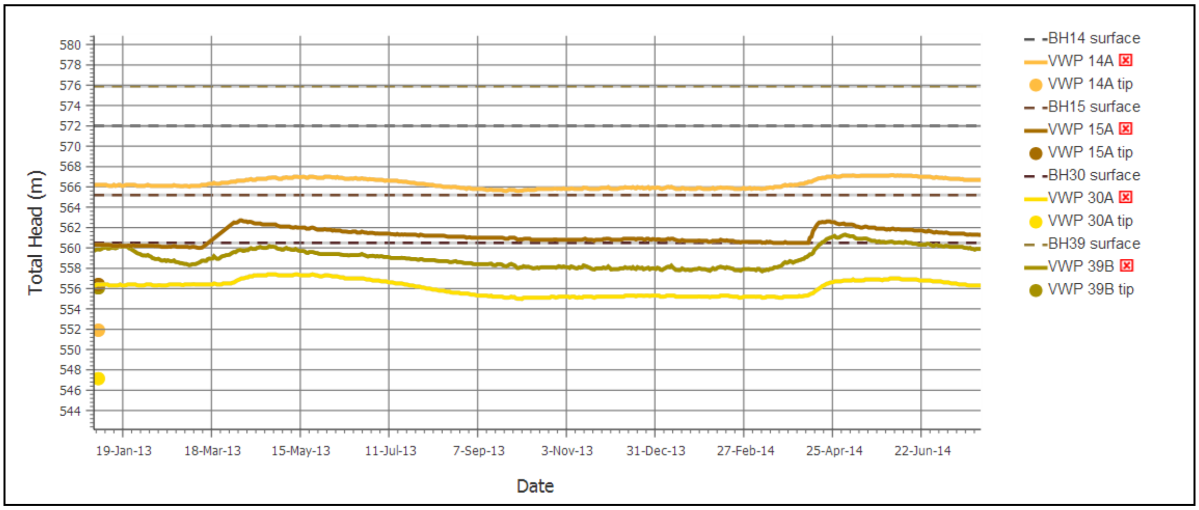


Chart 1 Unaffected groundwater levels, with regular seasonal (freshet) variation

Charts 2 through 4 below, illustrate examples of significant changes (reductions) to the previous typical background pattern recorded for a number of instruments, which is interpreted as the effect of nearby pumping wells. Chart 2 shows a plot of the typical seasonal unaffected background pattern (VWP15) in comparison to a series of VWP's located in the general vicinity of several pumping wells (PW4, PW6, PW13). The effects of the pumping wells on the groundwater pressure can be seen as a series of distinct drops in each data line as the various wells were brought into production, in this case being PW4 (late fall of 2007) and then PW6 and PW13 (early spring 2013). Charts 3 and 4 show similar typical pressure drops for PW1 and PW14, even though these two pumping wells were relatively low producers.

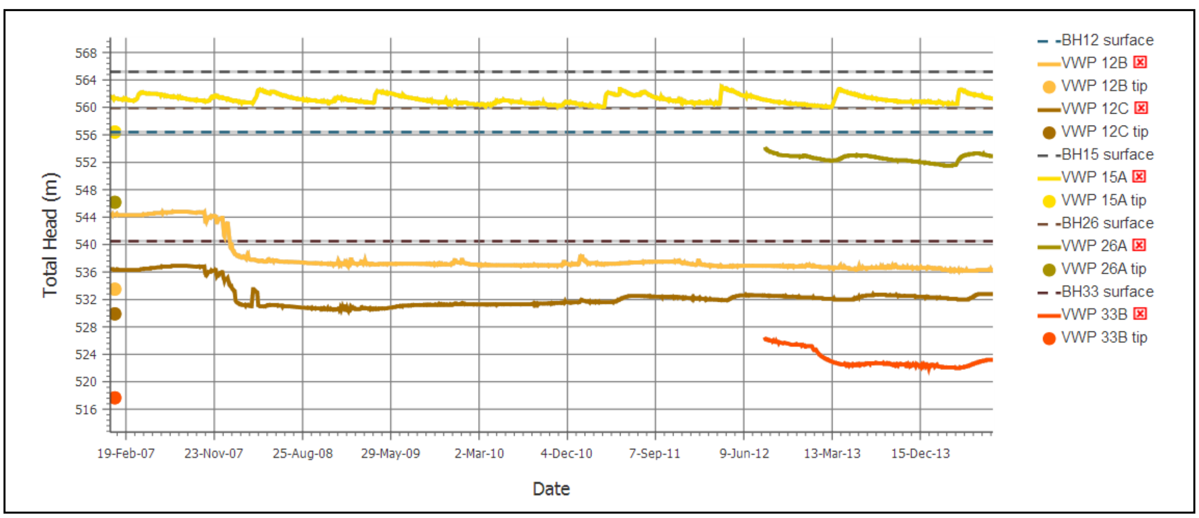


Chart 2 Pumping Well (PW4, PW6, PW13) effects (starting November 2007 & March 2013)

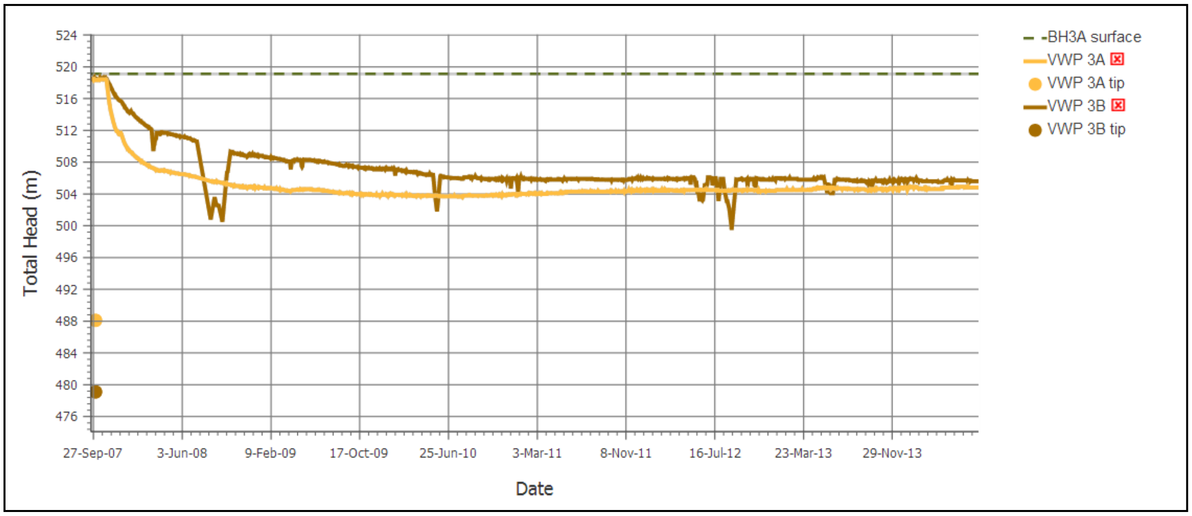


Chart 3 Pumping Well (PW1) drawdown effect (starting October 2007)

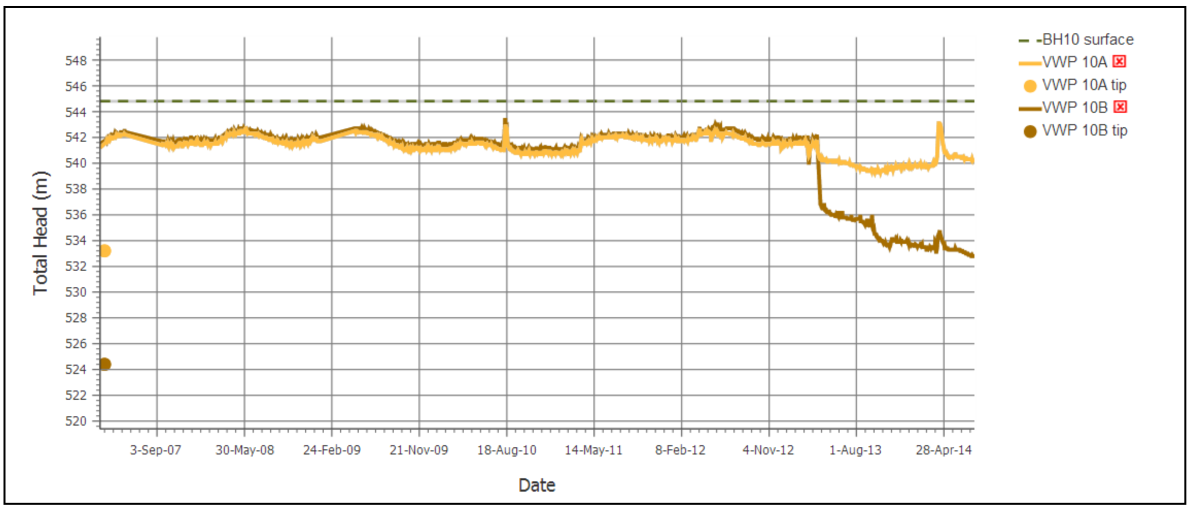


Chart 4 Pumping Well (PW11) drawdown effect (starting spring 2013)

Charts 5 through 7, following, illustrate examples of significant changes (reductions) to the previous typical background pattern recorded for a number of instruments, interpreted to represent the influence of horizontal drain discharge after installation. Chart 5 shows a plot of the background groundwater pattern for two of the longest serving groundwater instruments in West Quesnel (VWP3 near intersection of Betcher and Abbott, VWP 4 at the Voyageur School), originally installed in 2001. VWP4 is almost in the center of the landslide area, is a long way from the expected direct influence areas for either wells or horizontal drains. Except for a few sudden abrupt changes (interpreted to be the effect shifts in the slide mass and temporary local disturbance during nearby drilling operations), the ground water level at VWP4 has remained relatively constant and apparently unaffected in any significant way by dewatering effort to date. VWP 3 however is located adjacent to pumping well PW2. For a long time little significant variation occurred (other than minor local effects from PW2 as it cycled in and out of service), until the summer of 2013 when the start of a significant decline in groundwater pressure was observed. The timing of that decline coincided with the installation of horizontal drains at HD11.

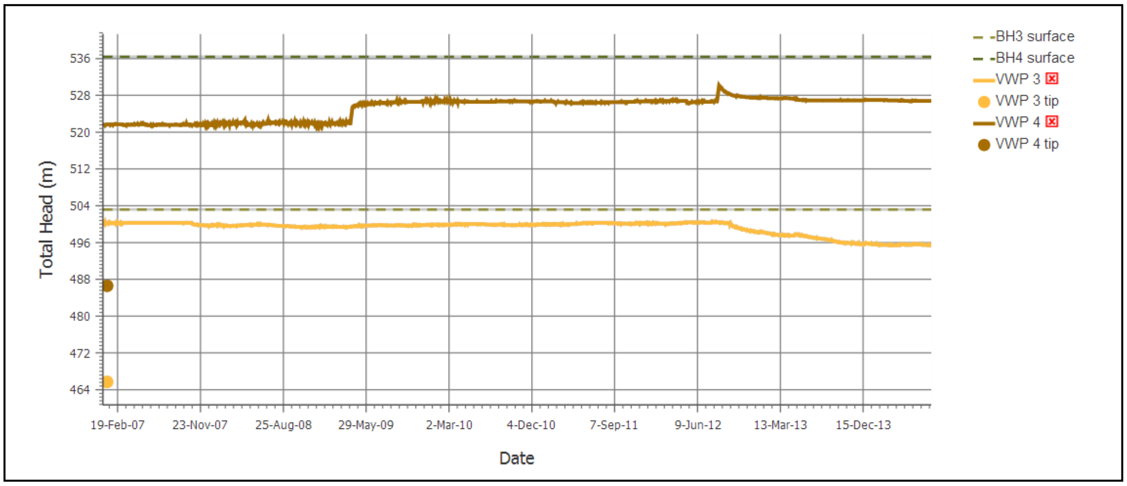


Chart 5 Groundwater decline at VWP3 corresponding with installation of HD11 (Aug 2012)

Charts 6 and 7 below show similar significant reductions in groundwater pressures likely attributed to horizontal drain installation for the areas north and south of Abbott Drive respectively, some of which continue to exhibit seasonal (spring freshet) fluctuations even at their reduced levels.

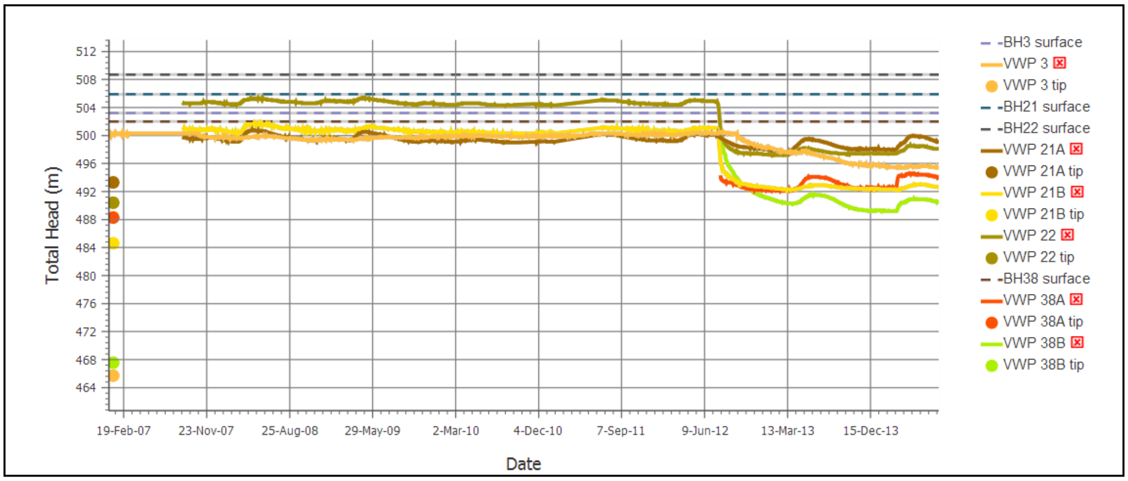


Chart 6 Inferred Horizontal Drain lowering of groundwater pressures (south of Abbott Drive)

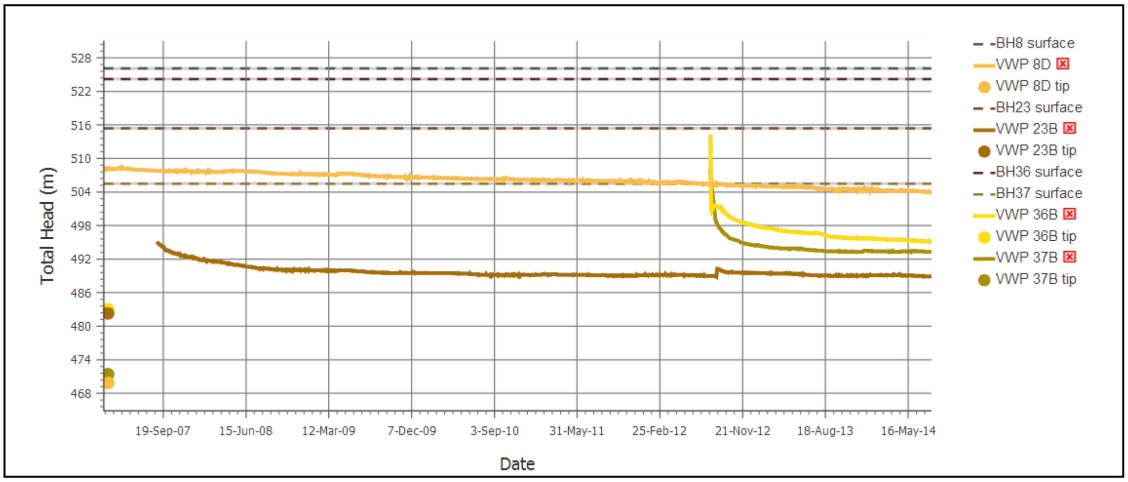


Chart 7 Inferred Horizontal Drain lowering of groundwater pressures (north of Abbott Drive)

In addition to the significant water flows and the ground instrument detections of gradually lowering groundwater pressures near the subsurface drain infrastructure, the most dramatic visible evidence of reduction in the water table in West Quesnel was as a result of the horizontal drain drilling. During and immediately following the completion of the horizontal drain drilling all the surface water in both Lewis Pond and Lower Blair Pond was eliminated: the ponds essentially dried up. The majority of the pond drawdown is thought to be associated with the high volume of water that was removed indirectly by HD8. At first it was thought that the dramatic productivity of HD8 was due solely to tapping into the stored water in the ponds. However, as very high flows from HD8 continue two years after installation, the locally high levels of groundwater in the area and the presence of those ponds is inferred to be primarily due to groundwater sources, now intercepted by the HD8 drains.

Section 5.4 and Appendix H contain more detailed descriptions on an instrument by instrument basis regarding observed changes in groundwater levels and an interpretation of how much of observed pressure declines may be due to installation of the subsurface dewatering pumping wells and horizontal drains. To date approximately 27 of the VWP installations have registered reductions in groundwater pressures that appear to be attributable to the subsurface dewatering program, with up to approximately 22 other instruments that may also be showing some slight influence from the dewatering system. The range of groundwater pressure reductions interpreted to be attributable to the implementation of the 2012 subsurface dewatering program varies from 0.5 m to 14 m, depending on location. Figure 9 presents a simplified plan view of the variation of those interpreted declines in groundwater pressure across the West Quesnel area. The greatest declines mostly coincide with the location of the higher producing wells in the northwest corner, and along the eastern portion of the landslide in the vicinity of the very productive horizontal drains.

6.2 GROUND MOVEMENT

Horizontal ground movement in West Quesnel has primarily been monitored by the use of Global Positioning System (GPS) surveys and slope inclinometer systems. Intermittent GPS surveys commenced in the September 1998. A more regular pattern of approximately quarterly surveys began in 2007. Conventional manual slope inclinometer surveys first began in November 2000 and ended in the Spring of 2009 with the shearing of the last serviceable instrument casing. Real time in-place slope inclinometer (IPSI) measurements commenced in the fall of 2012. The following sections summarize the ground movements observed, with a focus on comparisons of movement rates before and after implementation of the 2012 subsurface dewatering system. More detail on historical movement monitoring is available in various AMEC annual monitoring reports for the West Quesnel Land Stability Program (AMEC 2013, AMEC 2012).

Section 5.5 and Appendix I present the background information and data for the GPS surveys taken up to July 2014. Chart 8 below, shows the historic trend of annual movement (taken from approximately November to November of each year), up to July 2014 (partial year) for a typical (but worst case) movement hub: GPS 98-17. Since inception of the first surveys, a total of 661 mm of horizontal landslide related displacement has been measured. Depending on location, the average observed rate of movement has been on the order of 40 to 50 mm per year. More active years see approximately 50 to 90 mm of movement, and relatively low movement years typically exhibit less than 25 and sometimes less than 10 mm of movement. Previous manual slope inclinometer surveys have yielded similar results.

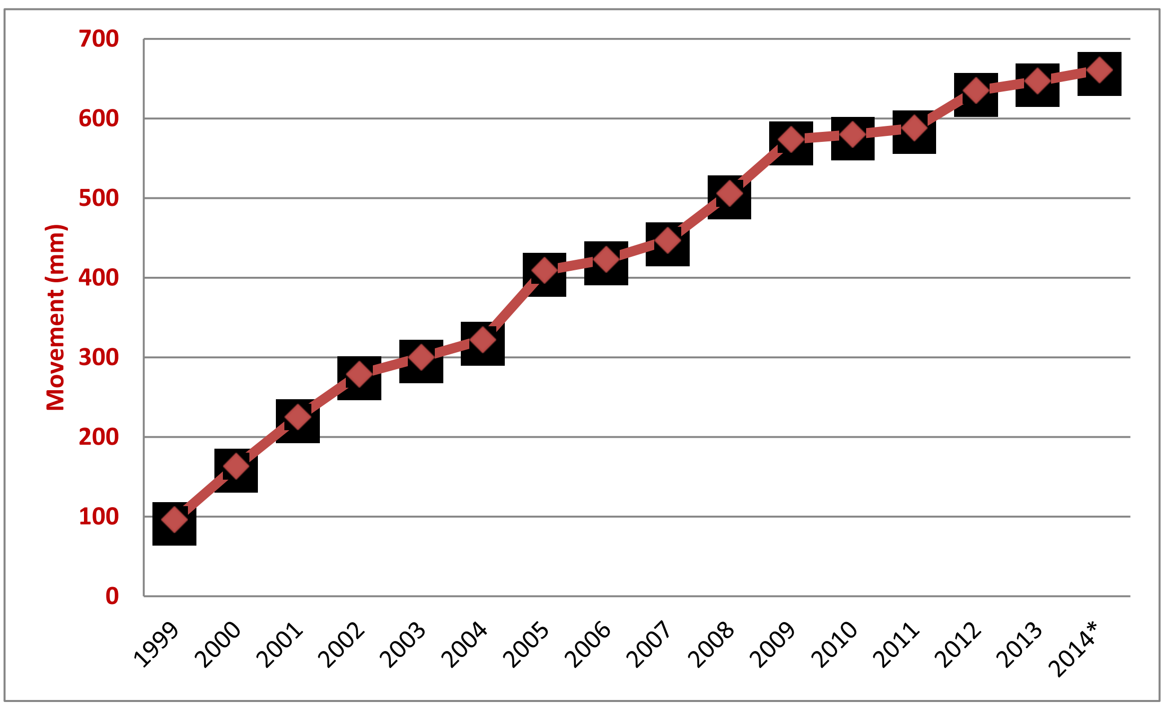


Chart 8 Typical movement (GPS 98-17) on an annual (Nov-Nov) basis (*only to July 2014)

After a ‘normal movement’ year of 47 mm of movement in 2012, both calendar years 2013 and 2014 (to date) exhibited movement rates typical of low movement years (12 mm and 14 mm respectively), amongst the lowest observed to date. Calendar years of 2010 and 2011 were very low (< 10 mm) movement years, but also corresponded with an extended period of significantly lower than average annual precipitation.

By way of comparison to typical historical movement rates, since the start of the subsurface dewatering system implementation in July 2012, GPS 98-17 hub exhibited 30 mm of movement during the first year (July 2012 to July 2013) of partial dewatering system operation but only 9 mm of movement over the most recent year (July 2013 to July 2014) of full system operation. The higher movement of 30 mm recorded in the first year may be attributable to a seasonal spike in annual movement due to freshet and recharge, that would have occurred prior to horizontal drain installation. The IPSI sensors in SI16 and 17 indicated up to 12 mm of movement occurred from October 2012 to July 2013, a much shorter in-service interval which likely missed the movement generated earlier in the year. However, for the period from July 2013 to July 2014, the IPSI’s measured between 8 and 11 mm of movement, essentially identical to that measured at GPS 98-17 over the same period.

Prior reporting has noted a strong correlation between precipitation, groundwater levels and rates of landslide movement. Typically it is expected that greater movements occur in or following wetter years where higher groundwater levels are generated. As noted in previous annual monitoring reporting (AMEC 2013, AMEC 2012) there is a stronger correlation between the amount of ground movement observed in any given year with the total precipitation experienced in the period 12 to 24 months prior, rather than with total precipitation experienced in the immediate 12 months prior. Chart 9 below, illustrates this one year time lag effect of prior (antecedent) precipitation.

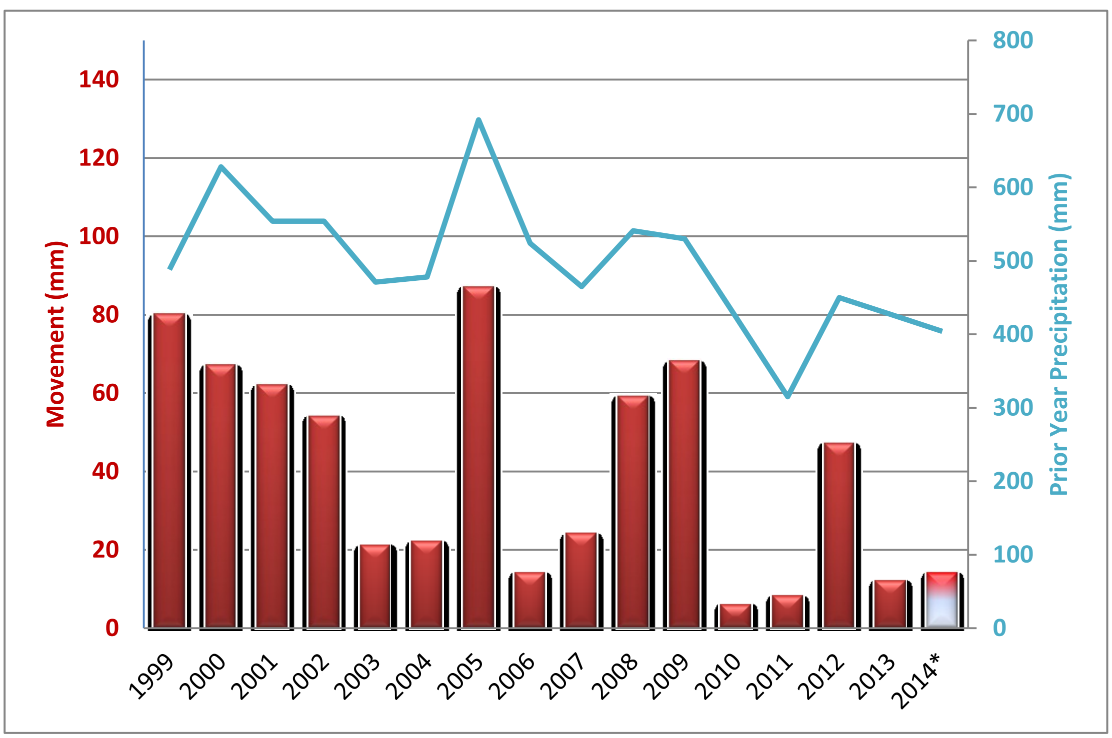


Chart 9 Correlation between annual movement (GPS 98-17) and antecedent precipitation

Even though the implementation period for the subsurface dewatering system beginning in mid 2012 corresponded with a time of below average antecedent precipitation, on the simple basis of the apparent correlation observed in Chart 9, one would have anticipated annual movement rates more typical of an ‘average’ year (40 to 50 mm) as opposed to the less than 20 mm observed for each of 2013 and 2014 to date. This discrepancy is interpreted to be an indication of the early effectiveness of the subsurface dewatering system.

Although antecedent precipitation is expected to be generally correlated with movement of the slide mass, it is really the resulting groundwater pressure that drives landslide movements. There is likely an over-riding and complicated weather effect related to the type of precipitation and seasonal climatic conditions and the degree of infiltration which occurs during precipitation events (during frozen/non-frozen and dry/saturated ground conditions) into the ground on subsequent groundwater pressures. There are also additional factors operating such as infiltration variability depending on surface moisture conditions and near surface groundwater conditions, lawn watering, variable losses from sewers and water systems and other unknown factors. In addition, in other landslide areas, the degree of infiltration has been found to vary with slide movement closing and opening tension areas combined with surface water and shallow groundwater flow paths.

With the implementation of more regular quarterly monitoring of ground movement and full time groundwater data collection in 2007, a closer examination of the relation between the two has been possible. Chart 10 below presents quarterly movement data in comparison to groundwater levels observed in a typical background piezometer installation (VWP14A), one that in the upper elevation reaches of the landslide area that is unlikely to have been affected by the dewatering system.

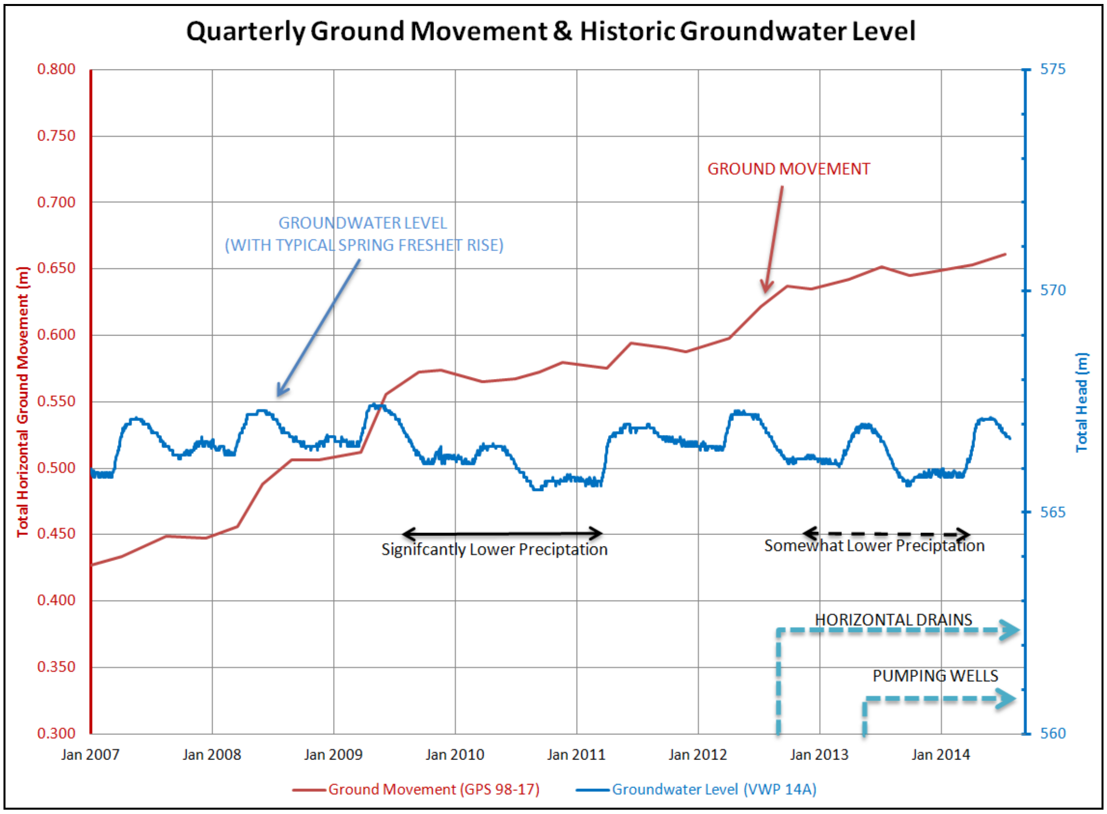


Chart 10 Relation between background groundwater pressure and ground movement

Chart 10 clearly shows the typical spring freshet peaks in groundwater pressure (the magnitude of which is likely driven by antecedent precipitation) and the corresponding increases in movement, largely taking place in the spring to early summer of each year. The chart also shows the reduced movement observed through the ‘drier’ period of 2010 and 2011 and its correlation to the reduced groundwater pressures over the same period. Of note though is the reduced rate of movement period in 2013 to 2014. Although this period corresponds with a period of somewhat lower than normal precipitation, background groundwater pressures were still significant with near normal freshet peaks. However, the amount of corresponding ground movement was significantly less than that observed in previous years having similar peaks. This reduction in movement may be attributable to the early effects of the dewatering system.

Further insight into the relation between groundwater pressures and landslide movement has been gained by the implementation of the IPSI system starting in the fall of 2012. While previously it was only possible to observe general movement trends on a quarterly basis and make inferences as to spring movement and spring freshet groundwater pressure rises, the real-time movement data from the IPSI’s provides more detail as to not only how the spring freshet related movement generally develops, but has also detected isolated movement spikes. Many of these spikes have been correlated with known water line breaks and short term rainfall events, demonstrating the ongoing influence of leaking utilities and near surface drainage on ground stability. Figure 10 at the end of the report provides a more detailed illustration of the day by day relation to ground movement detected by the IPSI’s and various weather conditions and utility events.

7.0 CONCLUSIONS

The West Quesnel subsurface dewatering system has only been in operation for a relatively short period of time, just over two years for the horizontal drains and approximately one and a half years for the pumping wells. The full system has only been in operation across one full spring freshet period. Although early yet, it is possible to make some initial conclusions about the performance of the dewatering system and its impact.

1. The pumping wells produce variable amounts of water, with the wells in the northwest corner of the landslide area being most productive. Although the pumping wells have a limited range over which they may be effective in drawing down adjacent groundwater pressures, noticeable reductions in surrounding groundwater pressures have been recorded at several locations.

2. The horizontal drains along the eastern toe area of the landslide typically produce ten times as much water as the pumping well system. They have been very effective at extracting groundwater and lowering groundwater pressures and the apparent near surface water table, particularly south of Lewis Drive. Horizontal drain installation site HD8 is operating at or over practical capacity.

3. Horizontal drain installations north of Lewis Drive have not been productive in terms of encountering nor removing groundwater. The overall effectiveness of horizontal drains is limited by their practical location and length of penetration.

4. Over the past 24 months (July 2012 to July 2014) there has been a measured reduction in groundwater pressures ranging between 0.5 and 15 m depending on location, which is considered to be attributable to the effects of the subsurface dewatering system operating in a highly variable but predominantly low permeability hydrogeological environment.

5. Over the last two calendar years (2013 and 2014 to date), measured horizontal landslide ground movements have been on the order of 12 and 14 mm respectively, considerably below the recorded longer term historical average of 40 to 50 mm per year.

6. During the most recent 12 months (ending July 2014) of full system operation, measured horizontal landslide ground movement has been less than 11 mm.

7. The period during which the subsurface dewatering system was implemented also coincided with a period of somewhat below average antecedent total precipitation (approximately 78 % of historical normal). However, natural background groundwater levels recorded above and in the uppermost western areas of the landslide were not significantly less than recorded for typical previous years when average or above average amounts of landslide movement were produced, particularly during spring freshet.

8. The period of system implementation coincided with a somewhat drier period, however the observed ground movements appear to have been less than what might have otherwise been expected. This is judged to be attributable to the 2012 subsurface dewatering system and a confirmation that the concept that groundwater level reduction in West Quesnel is effective in improving ground stability.

8.0 RECOMMENDATIONS

Although the 2012 subsurface dewatering system is operating as intended and is having a beneficial impact, it is still early in the implementation stages and the full effectiveness of the system, particularly over longer periods of average or above average total precipitation, remains to be tested. The instrumentation system has also demonstrated that groundwater pressures and ground stability are still very sensitive to the effects of surficial water infiltration, particularly that from short term storm events, surface runoff and water utility leaks; hence the need to implement the previously recommended surface drainage measures as the second part of the strategy to reduce groundwater pressures in West Quesnel. With this in mind, the following recommendations are provided:

1. Continue to operate, maintain and monitor the effectiveness of the subsurface dewatering system, and consider potential enhancements to the system on an annual basis.

2. Install additional pumping well capacity (three to four new wells) in the area of more highly productive and permeable sand and gravels in the northwest corner of the landslide area in West Quesnel.

3. Install additional horizontal drains from the toe of the slope in the vicinity of:

    a. the former Lewis Pond area;
    b. behind the Sikh Temple between HD8 and HD9;
    c. between HD9; and HD10
    d. west of Healy Street.

4. For the apparently intermittent or non-productive horizontal drain sites (HD5, HD6 and HD14), make sure the outlets of the drains are left exposed (re-expose if necessary), and re-slope the near vertical drill face (if not already partially collapsed) to match the natural ground slope in the area.

5. To ensure that the existing horizontal drains remain functional as intended, regularly monitor and maintain the cover backfill and repair damaged valves as needed.

6. Establish a full-time remote weather station in West Quesnel dedicated to continuous recording of total precipitation, barometric pressure, air temperature and ground temperature; connect to the current remote groundwater and movement instrumentation and data management system.

7. Proceed with comprehensive surface drainage improvements and controls generally envisioned as “Phase 3” of the West Quesnel Dewatering Program (Morgenstern, 2005), specifically considering the following elements:

    a. A vigorous program of surface drainage control and water use management to minimize ponding and infiltration from natural runoff and artificial sources of water.

    b. Camera inspection of all existing storm drains and sewer utilities in order to detect and expedite repair of breaks that allow water infiltration.

   c. Completion and enhancements to the storm water collection system in West Quesnel.

   d. Providing a permanent and positive gravity drainage outlet (trenches and/or buried culverts) from the base of the former Lewis Pond area.

   e. Draining and eliminating or otherwise renovating all the current pond areas in West Quesnel such that they are not sources of surface water collection and groundwater recharge, but instead would also allow enhanced discharge to a controlled storm water collection system.

   f. A program of semi-continuous water supply system leak detection, including zone based flow monitoring.

8. Consider stabilizing the toe area of the Baker Creek Slide area, identified in previous studies.

9.0 CLOSURE

This report has been prepared for the exclusive use of the City of Quesnel and their representatives for specific application to West Quesnel Land Stability Program. Any use which a third party makes of this report, or any reliance on or decisions made based on it, are the responsibility of such third parties. AMEC accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this report.

This report was prepared in accordance with generally accepted geotechnical engineering principles and practice. No other warranty, expressed or implied, is made.

Please do not hesitate to contact the undersigned at (250) 564-3243 should you have any questions or require further information.

AMEC Environment & Infrastructure
A division of AMEC Americas Limited

Reviewed by:

Luke Marquis, EIT
Geotechnical Engineer

Greg Reid, P. Eng. P. Geo, FEC FGC
Associate Geological Engineer

Nov. 21/2014

Dmitri Ostritchenko, P. Eng.
Geotechnical Engineer

21/11/2014

Nick C. Polysou, P.Eng.
Senior Associate, Geotechnical Engineer

10.0 REFERENCES

AMEC (2014). “West Quesnel Stability Program Annual Monitoring Report – 2013”, 11 March 2014.

AMEC (2013). “West Quesnel Stability Program Annual Monitoring Report – 2012”, 2 April 2013.

AMEC (2012). “West Quesnel Stability Program Annual Monitoring Report – 2011”, 18 January 2012.

AMEC (2011). “West Quesnel Stability Program Annual Monitoring Report – 2010”, 4 February 2011.

AMEC (2010). “West Quesnel Stability Program Annual Monitoring Report – 2009”, 1 February 2010.

AMEC (2009). “West Quesnel Stability Program Annual Monitoring Report – 2008”, 9 March 2009.

AMEC (2008). “Trial Dewatering West Quesnel Land Stability Program Quesnel, BC”, May 2008.

AMEC (2007). “West Quesnel Land Stability Study Volumes 1&2”, May 2007.

AMEC (2006). “West Quesnel Land Stability Project Geotechnical & Hydrogeological Programs Progress Report, 2006 & 2007 Work Plan”, 1 December 2006.

AMEC (2005). “On-Going Monitoring-Update Report For 2004 West Quesnel Land Stability Study”, 15 April 2005.

AMEC (2004). “West Quesnel INSAR Deformation Assessment Quesnel, British Columbia”, 22 November 2004.

AMEC (2004). “Pilot Dewatering Well Test West Quesnel Land Stability Study Quesnel, British Columbia”, 28 May 2004.

AMEC (2004). “On-Going Monitoring-Update Report West Quesnel Land Stability Study”, 20 January 2004.

AMEC (2002). “November Slope Inclinometer Installation Readings West Quesnel Land Stability Study”, 12 December 2002.

AMEC (2002). “West Quesnel Land Stability Study Quesnel, British Columbia”, 25 October 2002.

AMEC (2001). “Stage 1 Status Report West Quesnel Land Stability Study Quesnel BC”, 13 August 2001.

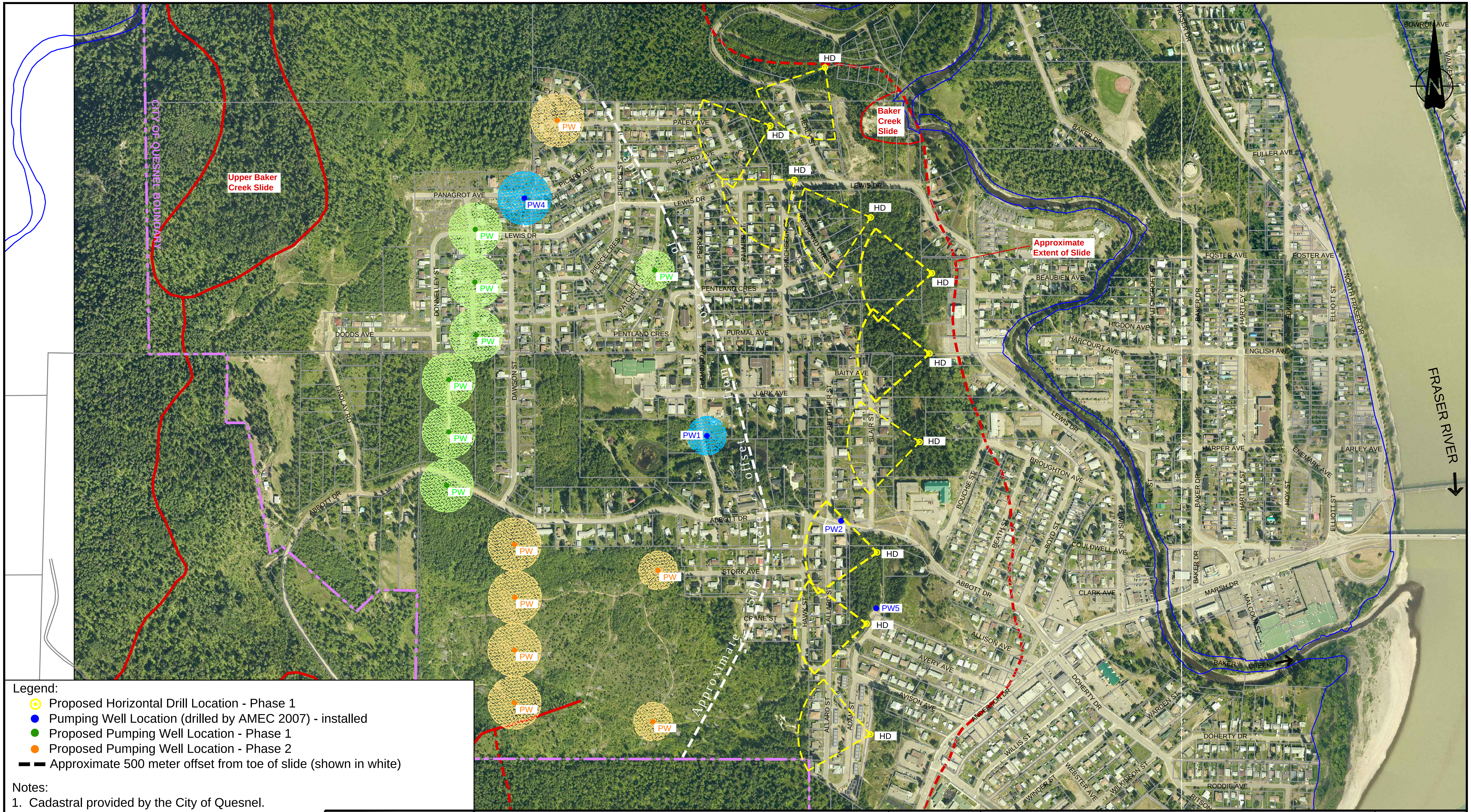
AMEC (2001). “Project Update -March Slope Inclinometer Installation Readings West Quesnel Land Stability Study”, 16 March 2001.

AMEC (2001). “Project Update West Quesnel Stability Study”, 26 January 2001.

Morgenstern (2005). “West Quesnel Land Stability Program”, Letter from N. R. Morgenstern to Mr. Dwayne Meredith, Emergency Management BC, 11 October 2005.

FIGURES

Figure 1	Conceptual Subsurface Dewatering System
Figure 2	2012 As-Built Site Plan
Figure 3	Instrumentation Data Logger Site Plan
Figure 4	Overall Instrumentation Site Plan
Figure 5A	Data Logger Connection Schematic (Station 01 through 10)
Figure 5B	Data Logger Connection Schematic (Station 11 through 20)
Figure 5C	Data Logger Connection Schematic (Station 21 through 30)
Figure 6	Incremental GPS Movement Vector Plan
Figure 7	Simplified GPS & IPSI Movement Vector Plan
Figure 8	Pumping Well & Horizontal Drain Productivity
Figure 9	Groundwater Drawdown
Figure 10	Daily IPSI Movement & Precipitation



Legend:
- Proposed Horizontal Drill Location - Phase 1
- Pumping Well Location (drilled by AMEC 2007) - installed
- Proposed Pumping Well Location - Phase 1
- Proposed Pumping Well Location - Phase 2
- Approximate 500 meter offset from toe of slide (shown in white)

Notes:
1. Cadastral provided by the City of Quesnel.
2. This drawing must be read in conjunction with AMEC Environment & Infrastructure Geotechnical Report, "2012 Subsurface Dewatering System."

0m 50 100 150 200 250 300
1 : 7500

West Quesnel Land Stability Program

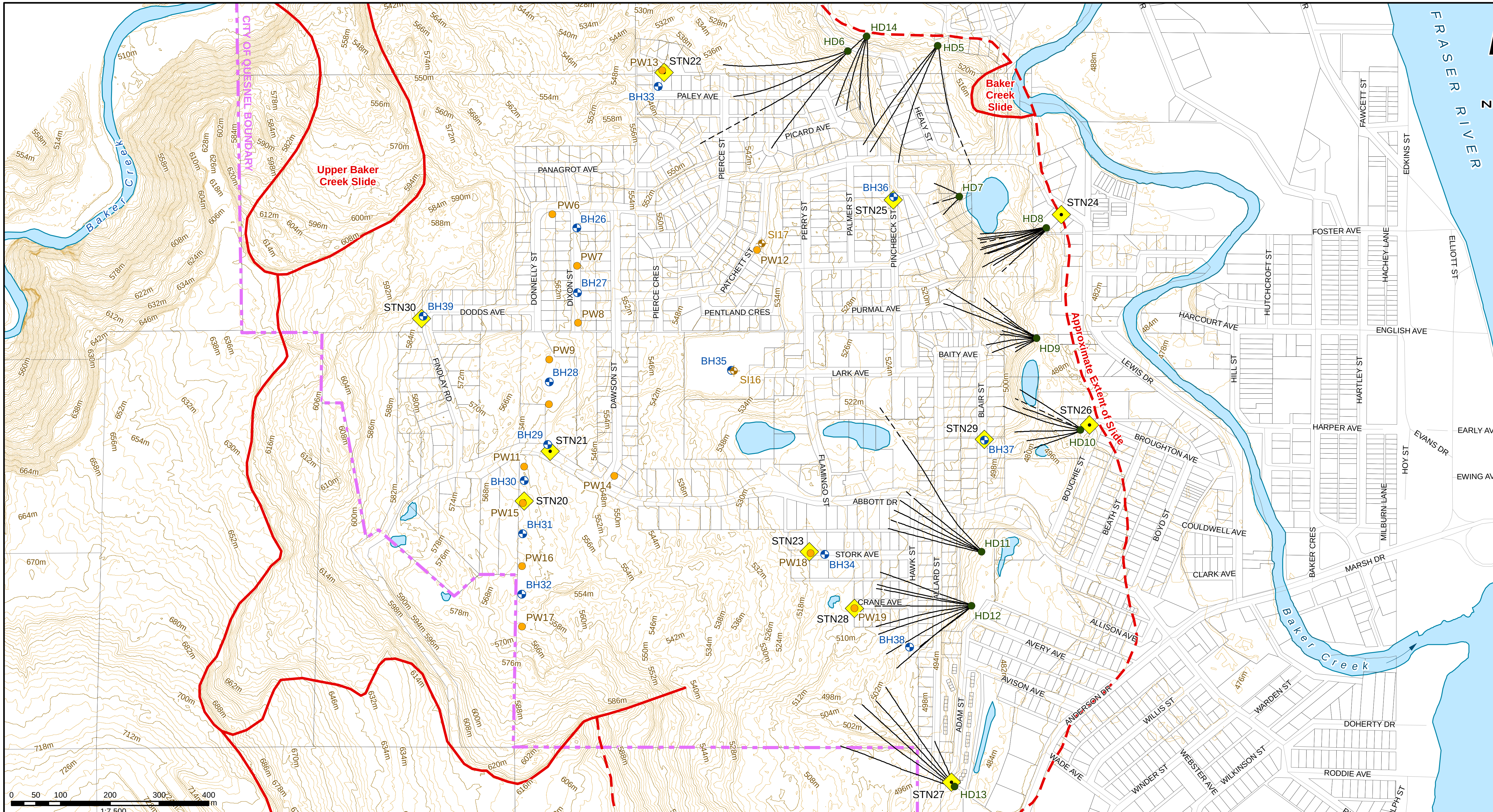
CLIENT: CITY OF QUESNEL

AMEC Earth & Environmental
3456 Opie Crescent
Prince George, BC, CANADA V2N 2P9
Tel. (250) 564-3243
Fax (250) 562-7045

DWN BY:	SR/BB
CHK'D BY:	DO
DATUM:	NAD83
PROJECTION:	UTM Zone 10
SCALE:	1:7500
TITLE	CONCEPTUAL SUBSURFACE DEWATERING SYSTEM
PROJECT	2012 SUBSURFACE DEWATERING SYSTEM
DATE:	NOVEMBER 2014
PROJECT NO:	KX0439740
REV. NO.:	A
	FIGURE 1

C:\Users\ben.brown\appdata\local\temp\AcPublish_5232\KX0439740-Figure1-ConceptualSubsurfaceDewateringSystem.dwg – Figure1 – Nov. 14, 2014 10:40am – benjamin.brown

This drawing was originally produced in colour.



Legend

- Horizontal Drain (2012)
- Surveyed Horizontal Drain Trace
- Approximated Horizontal Drain Trace
- Borehole - Vibrating Wire (2012)
- Pumping Well (2012)
- Slope Inclinometer (2012)
- Instrumentation Data Logger Station (2012)
- Slide Extent
- Slide Extent (Approximate)
- Approximate Pond Location

West Quesnel Land Stability Program

CLIENT:	CITY OF QUESNEL
	AMEC Environment & Infrastructure 3456 Opie Crescent Prince George, BC, CANADA V2N 2P9
DWN BY:	BB
CHK'D BY:	LM
DATUM:	NAD 83
PROJECTION:	UTM Zone 10
SCALE:	1:7,500
DATE:	NOVEMBER 2014
PROJECT NO.:	KX0439740
REV NO.:	A

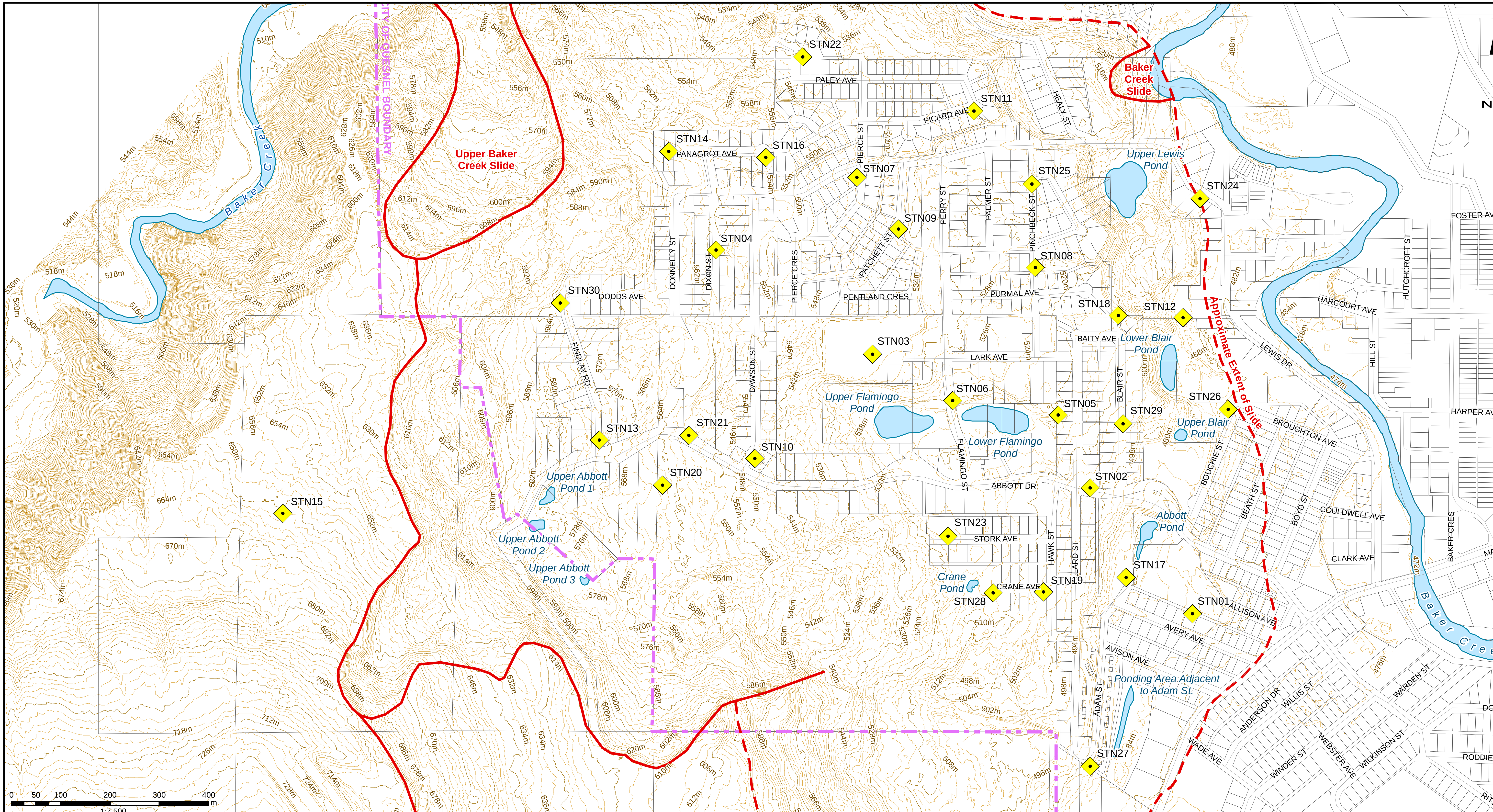
2012 AS-BUILT SITE PLAN

2012 SUBSURFACE DEWATERING SYSTEM

FIGURE 2

S:\Internal\KX04397-WQLS-GIS\0_KX0439741.3\KX0439740-Figure2-2012AsBuiltSitePlan.mxd

This drawing was originally produced in colour.



Legend

- Instrumentation Data Logger Station
- Slide Extent
- Slide Extent (Approximate)
- Approximate Pond Location

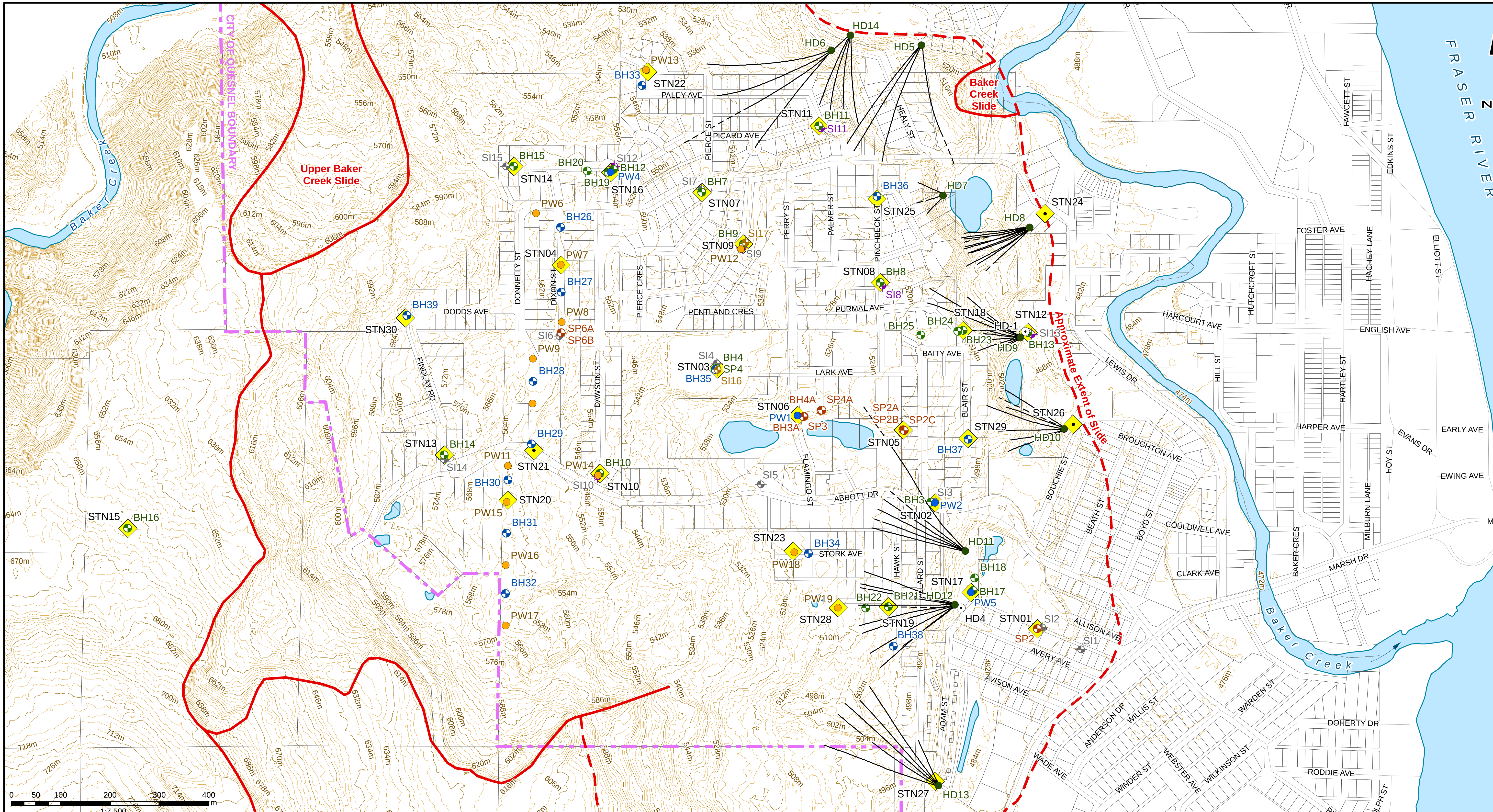
West Quesnel Land Stability Program

CLIENT: CITY OF QUESNEL	DWN BY: BB CHK'D BY: LM	INSTRUMENTATION DATA LOGGER SITE PLAN	DATE: NOVEMBER 2014 PROJECT NO.: KX0439740
AMEC Environment & Infrastructure 3456 Opie Crescent Prince George, BC, CANADA V2N 2P9	DATUM: NAD 83 PROJECTION: UTM Zone 10 SCALE: 1:7,500	2012 SUBSURFACE DEWATERING SYSTEM	REV NO.: A FIGURE 3

amec

S:\Internal\KX04397-WQLS-GIS\0_KX0439741.3\KX0439740-Figure3-InstrumentationDataLoggerSitePlan.mxd

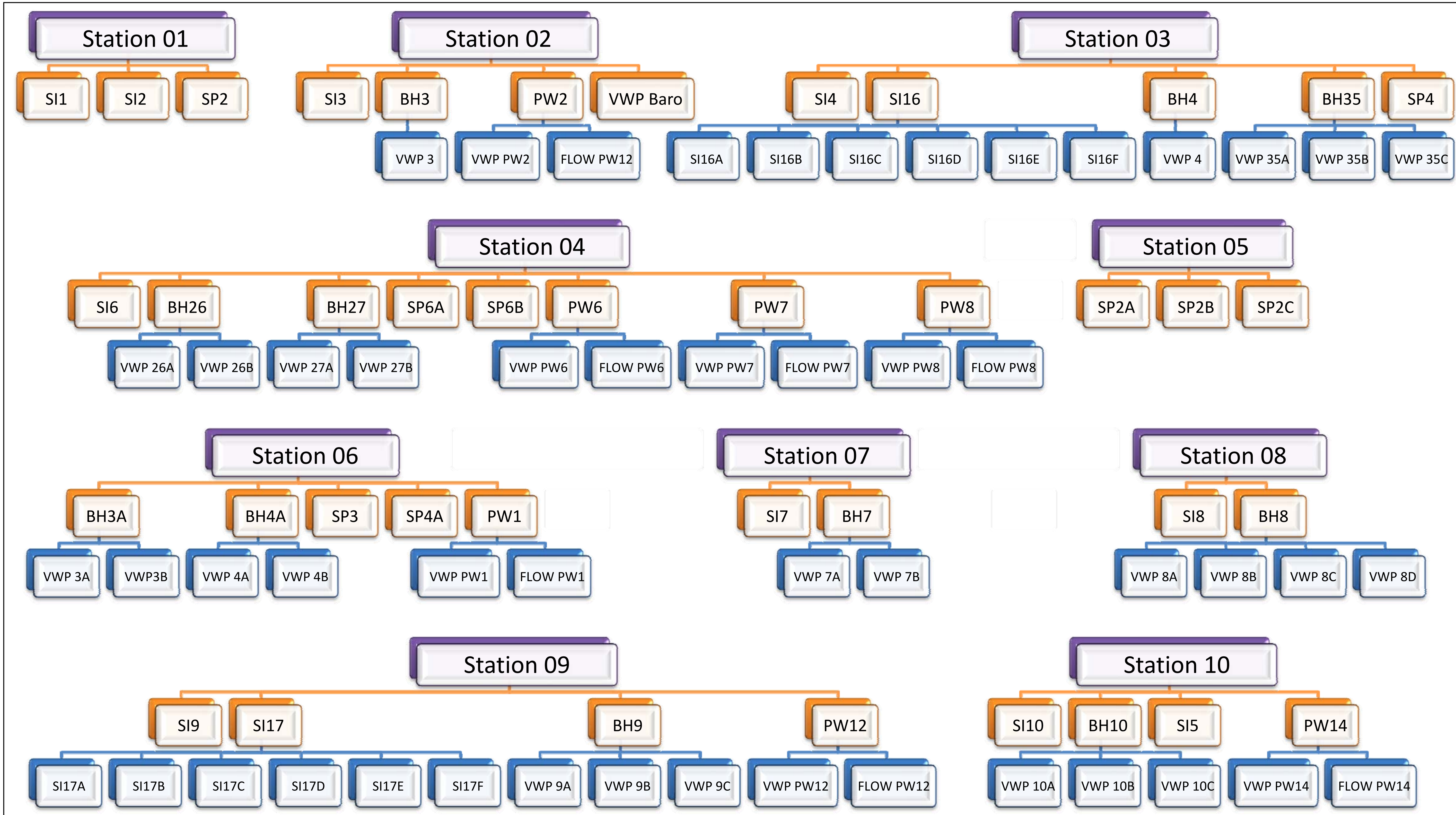
This drawing was originally produced in colour.



Legend Horizontal Drain (2012) Horizontal Drain (2007) Borehole - Vibrating Wire (2012) Borehole - Vibrating Wire (2001-2007) Borehole - Stand Pipe (2001-2003) Pumping Well (2012) Pumping Well (2007) Slope Inclinometer (2012) Slope Inclinometer (2005) Slope Inclinometer (Blocked, 2000-2006) Instrumentation Data Logger Station Approximate Pond Location Slide Extent Slide Extent (Approximate) Surveyed Horizontal Drain Trace Approximated Horizontal Drain Trace	West Quesnel Land Stability Program	CLIENT: CITY OF QUESNEL AMEC Environment & Infrastructure 3456 Opie Crescent Prince George, BC, CANADA V2N 2P9 amec	DWN BY: BB CHK'D BY: LM DATUM: NAD 83 PROJECTION: UTM Zone 10 SCALE: 1:7,500	OVERALL INSTRUMENTATION SITE PLAN 2012 SUBSURFACE DEWATERING SYSTEM	DATE: NOVEMBER 2014 PROJECT NO.: KX0439740 REV NO.: A FIGURE 4

S:\Internal\KX04397-WQLS-GIS\0_KX0439741.3\KX0439740-Figure4-OverallInstrumentationSitePlan.mxd

This drawing was originally produced in colour.



amec
AMEC Environment & Infrastructure
3456 Opie Crescent
Prince George, BC, CANADA, V2N 2P9
Tel. (250) 564-3243
Fax. (250) 562-7045

West Quesnel
Land Stability Program

DATE PREPARED: NOVEMBER 2014

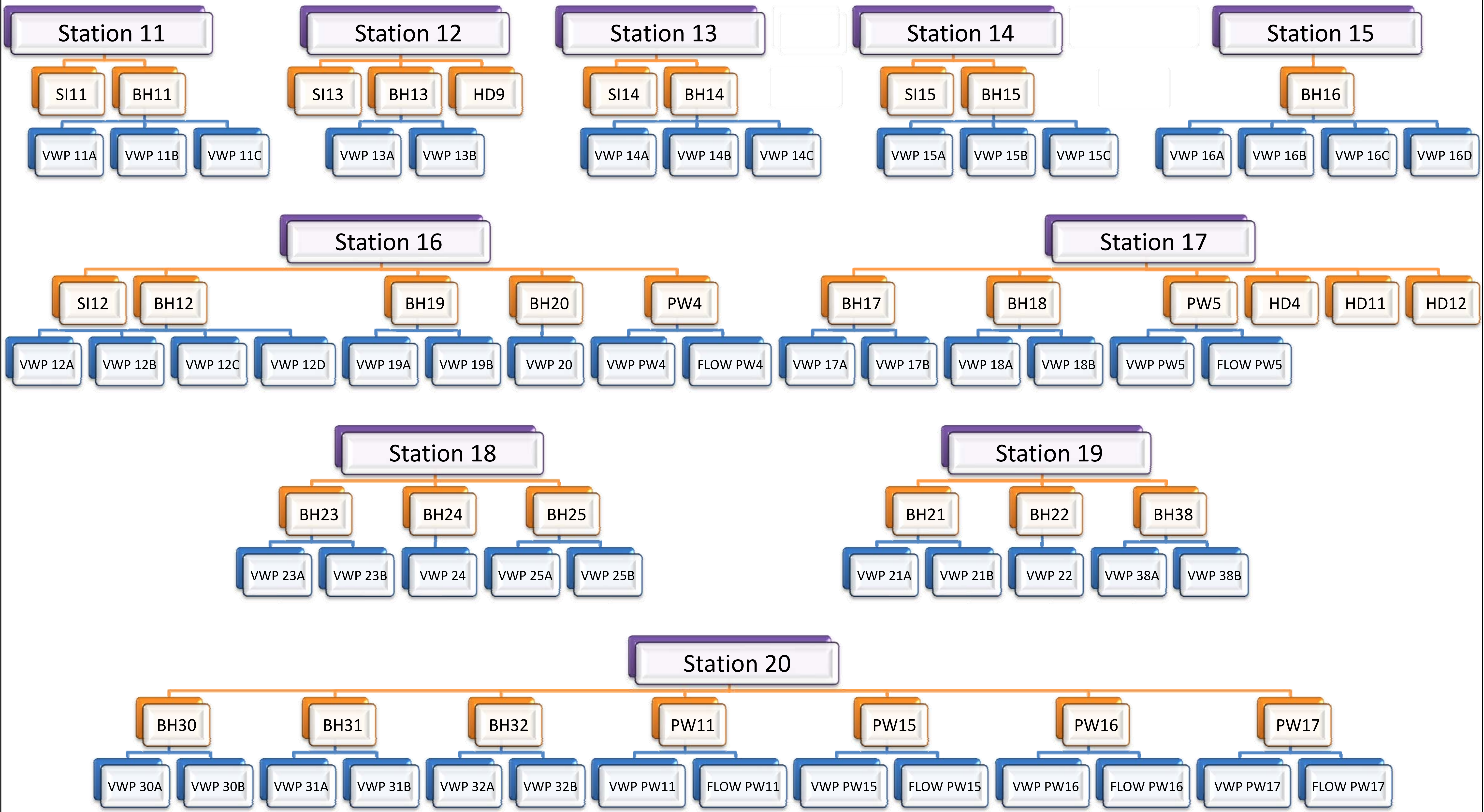
SCALE: NTS

PREPARED BY: DO

PROJECT No: KX0439740

DATA LOGGER CONNECTION SCHEMATIC
(STATION 01 THROUGH STATION 10)
2012 SUBSURFACE DEWATERING SYSTEM

Figure 5A



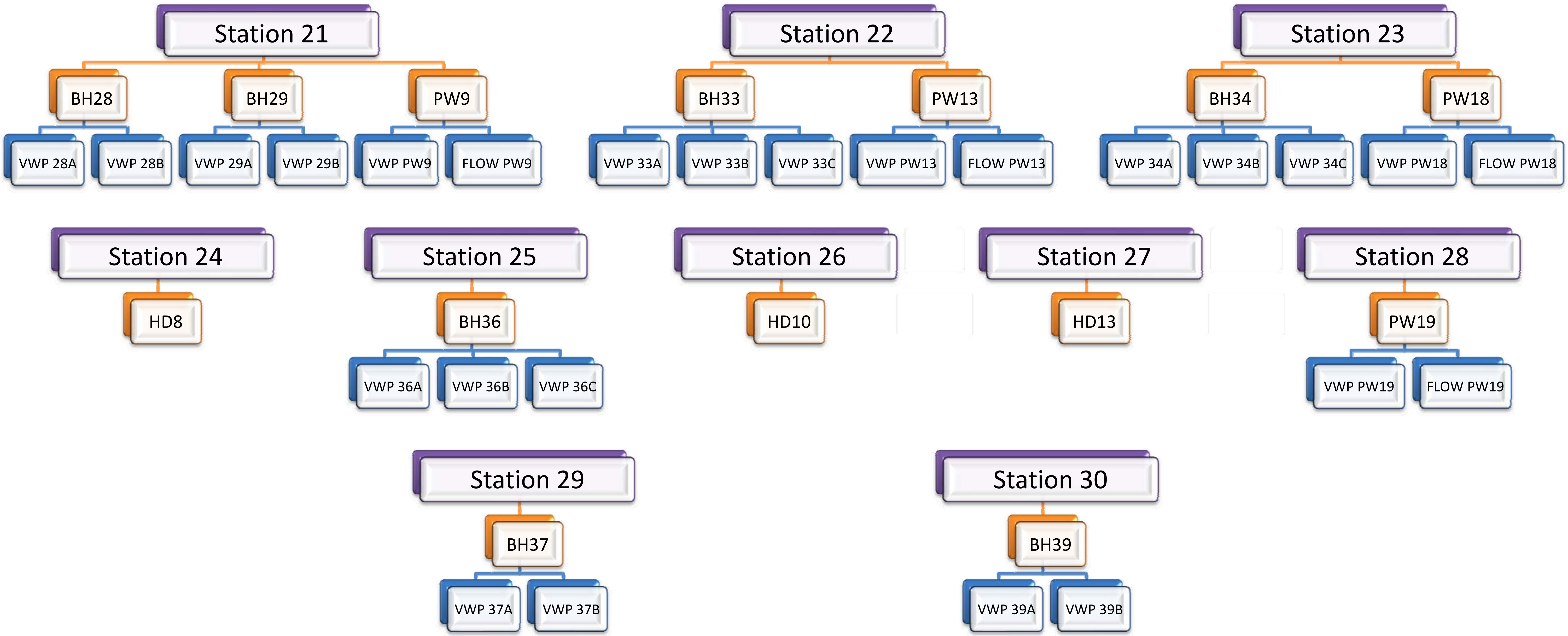
amec
AMEC Environment & Infrastructure
3456 Opie Crescent
Prince George, BC, CANADA, V2N 2P9
Tel. (250) 564-3243
Fax. (250) 562-7045

West Quesnel Land Stability Program

DATE PREPARED: NOVEMBER 2014
SCALE: NTS
PREPARED BY: DO
PROJECT No: KX0439740

DATA LOGGER CONNECTION SCHEMATIC (STATION 11 THROUGH STATION 20) 2012 SUBSURFACE DEWATERING SYSTEM

Figure 5B



AMEC Environment & Infrastrucure
3456 Opie Crescent
Prince George, BC, CANADA, V2N 2P9
Tel. (250) 564-3243
Fax. (250) 562-7045

West Quesnel
Land Stability Program

DATE PREPARED: NOVEMBER 2014

SCALE: NTS

PREPARED BY: DO

PROJECT No: KX0439740

DATA LOGGER CONNECTION SCHEMATIC
(STATION 21 THROUGH STATION 30)
2012 SUBSURFACE DEWATERING SYSTEM

Figure 5C

GPS Monitoring Dates

Inital September 1998

#1 December 1998	#11 November 2003	#21 November 2008	#31 June 2011	#41 November 2013
#2 April 1999	#12 January 2005	#22 March 2009	#32 October 2011	#42 April 2014
#3 December 1999	#13 March 2006	#23 June 2009	#33 November 2011	#43 July 2014
#4 February 2000	#14 November 2006	#24 September 2009	#34 April 2012	#44
#5 May 2000	#15 April 2007	#25 November 2009	#35 July 2012	#45
#6 December 2000	#16 August 2007	#26 March 2010	#36 September 2012	#46
#7 May 2001	#17 December 2007	#27 July 2010	#37 December 2012	#47
#8 December 2001	#18 March 2008	#28 September 2010	#38 April 2013	#48
#9 May 2002	#19 June 2008	#29 November 2010	#39 July 2013	#49
#10 October 2002	#20 August 2008	#30 April 2011	#40 October 2013	#50

Legend

GPS Hubs Installed

- September 1998
- December 2001
- November 2006
- June 2008
- November 2013

GPS Hub Vector

GPS98-02

554mm - Total horizontal movement in mm at surface
-74mm - Total vertical movement in mm at surface
Positive (+) elevation shows a rise in elevation
Negative (-) elevation shows a drop in elevation

Notes:
1. GPS Hub Data provided by McElhanney July 2014.
2. Cadastral provided by City of Quesnel.

West Quesnel Land Stability Program

CLIENT: CITY OF QUESNEL

AMEC Environment & Infrastructure
3456 Opie Crescent
Prince George, BC, CANADA V2N 2P9

amec

DWN BY:	BB
CHK'D BY:	LM
DATUM:	NAD 83
PROJECTION:	UTM Zone 10
SCALE:	1:5,000

TITLE: INCREMENTAL GPS MOVEMENT VECTOR PLAN

PROJECT: 2012 SUBSURFACE DEWATERING SYSTEM

DATE: NOVEMBER 2014

PROJECT NO.: KX0439740

REV NO.: A

FIGURE 6

S:\Internal\KX04397-WQLS-GIS\0_KX0439741.3\KX0439740-Figure6-IncrementalGPSMovementVectorPlan.mxd

This drawing was originally produced in colour.

Notes:
1. GPS Hub Data provided by McElhanney July 2014.
2. Cadastral provided by City of Quesnel.

GPS Monitoring Dates

Inital September 1998

#1 December 1998	#11 November 2003	#21 November 2008	#31 June 2011	#41 November 2013
#2 April 1999	#12 January 2005	#22 March 2009	#32 October 2011	#42 April 2014
#3 December 1999	#13 March 2006	#23 June 2009	#33 November 2011	#43 July 2014
#4 February 2000	#14 November 2006	#24 September 2009	#34 April 2012	#44
#5 May 2000	#15 April 2007	#25 November 2009	#35 July 2012	#45
#6 December 2000	#16 August 2007	#26 March 2010	#36 September 2012	#46
#7 May 2001	#17 December 2007	#27 July 2010	#37 December 2012	#47
#8 December 2001	#18 March 2008	#28 September 2010	#38 April 2013	#48
#9 May 2002	#19 June 2008	#29 November 2010	#39 July 2013	#49
#10 October 2002	#20 August 2008	#30 April 2011	#40 October 2013	#50

Legend

GPS Hubs Installed
- September 1998
- December 2001
- November 2006
- June 2008
- November 2013

GPS Hub Vector

GPS98-02 (**554mm**, -74mm)

September 1998 to December 2001 — December 2001 to November 2006 — November 2006 to July 2008 — July 2008 to November 2013 — November 2013 to July 2014

Total vertical movement in mm at surface
Positive (+) elevation shows a rise in elevation
Negative (-) elevation shows a drop in elevation
Total horizontal movement in mm at surface

In-place Inclinometer Initialized

SI16 (**18.6mm**, 50.8m) (September 20, 2012)
SI17 (**23.4mm**, 65.0m) (October 16, 2013)

In-place Inclinometer Vector

Total Horizontal Movement
SI16 (**18.6mm**, 50.8m)
Movement depth below surface in m
Total horizontal movement in mm

West Quesnel Land Stability Program

CLIENT: CITY OF QUESNEL

AMEC Environment & Infrastructure
3456 Opie Crescent
Prince George, BC, CANADA V2N 2P9

amec

DWN BY:	BB
CHK'D BY:	LM
DATUM:	NAD 83
PROJECTION:	UTM Zone 10
SCALE:	1:5,000

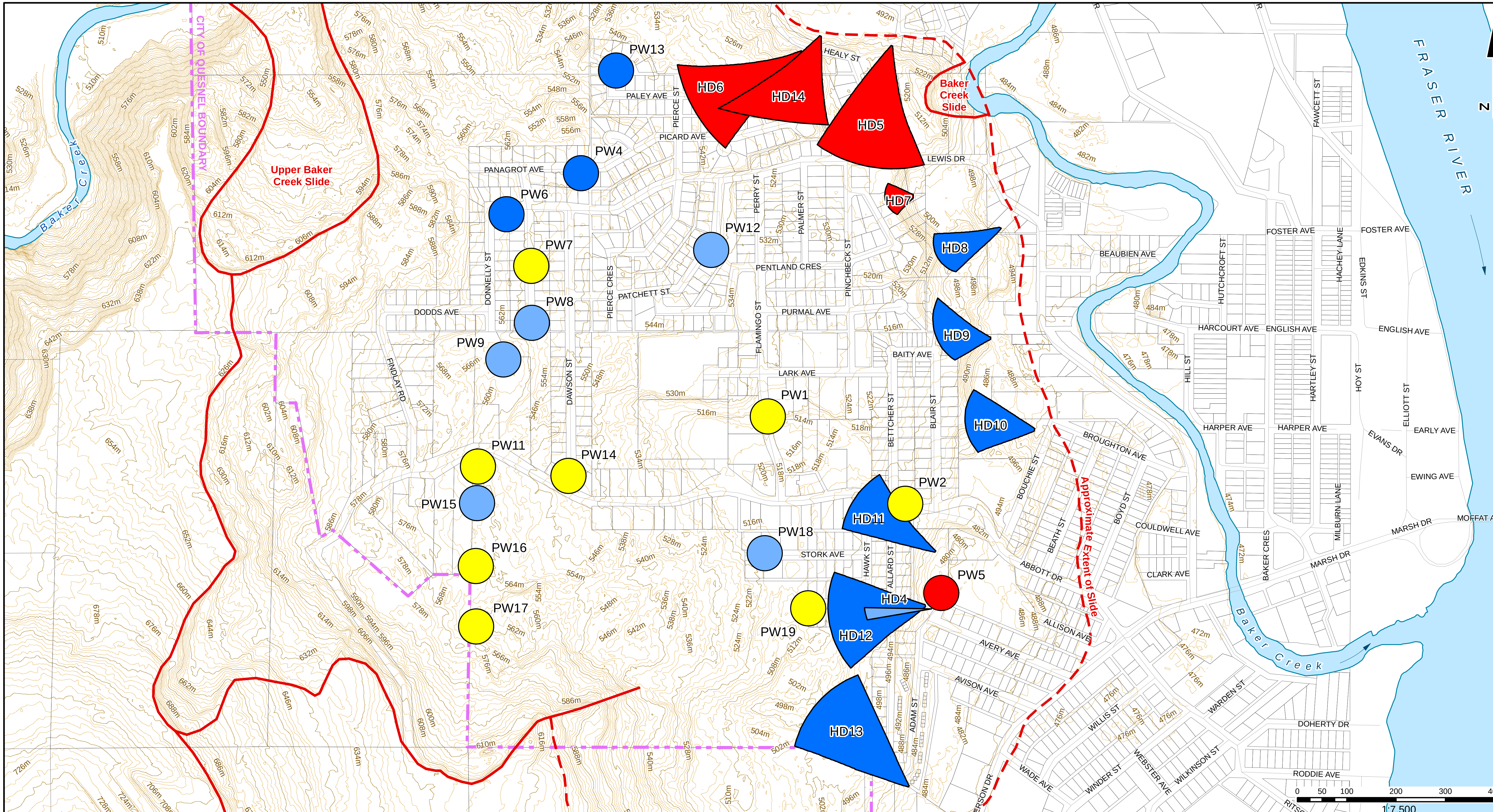
TITLE: SIMPLIFIED GPS & IPSI MOVEMENT VECTOR PLAN

PROJECT: 2012 SUBSURFACE DEWATERING SYSTEM

DATE: NOVEMBER 2014
PROJECT NO.: KX0439740
REV NO.: A
FIGURE 7

S:\Internal\KX04397-WQLS-GIS\0_KX0439741.3\KX0439740-Figure7-SimplifiedGPS&IPSIMovementVectorPlan.mxd

This drawing was originally produced in colour.



Horizontal Drain / Pumping Well Productivity

Flow (L/Day)

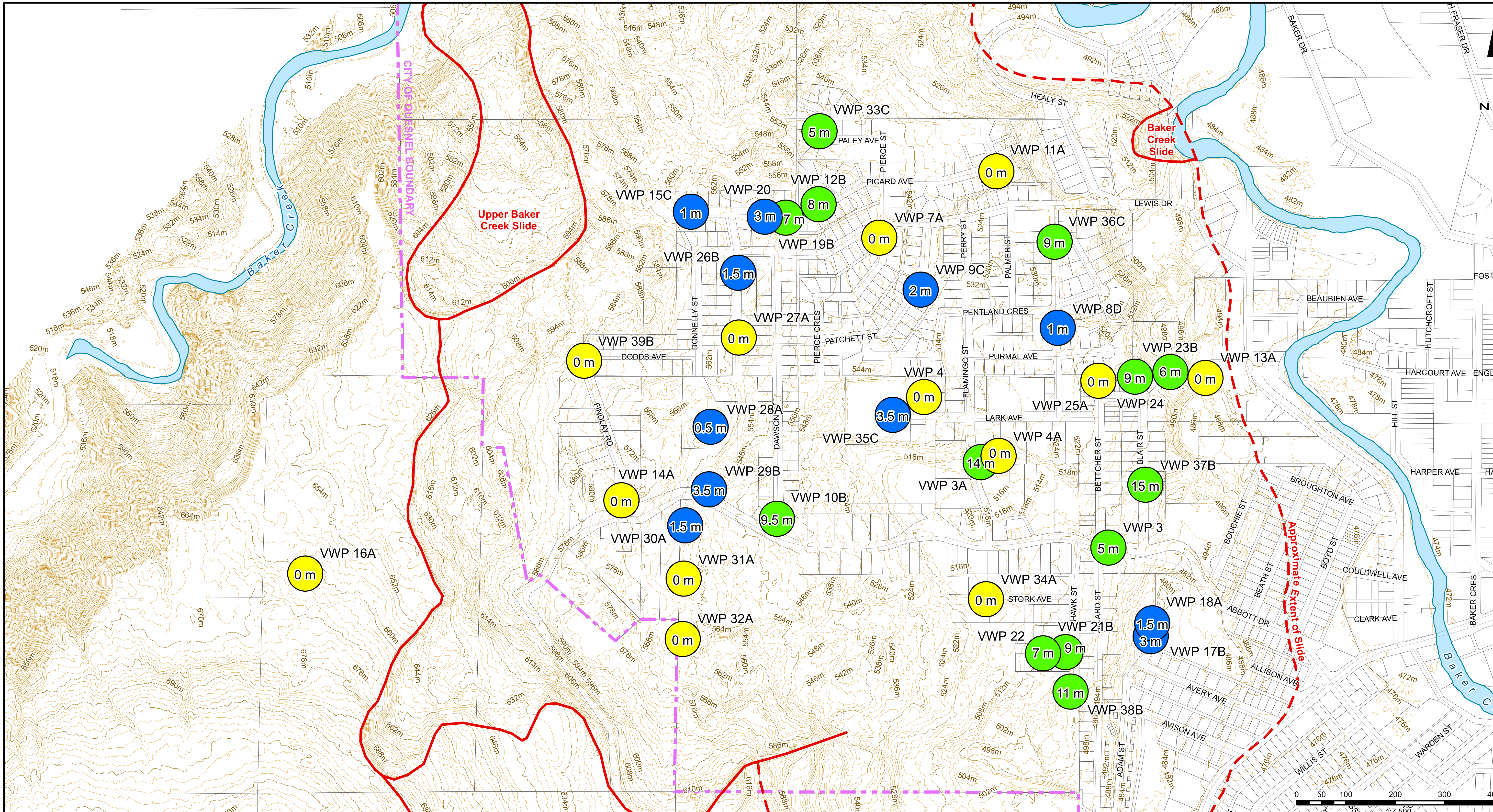
- < 10
- 10 - 500
- 501 - 5000
- > 5000

West Quesnel Land Stability Program

CLIENT: CITY OF QUESNEL	DWN BY: BB	PUMPING WELL & HORIZONTAL DRAIN PRODUCTIVITY	DATE: NOVEMBER 2014
	CHK'D BY: DO		PROJECT NO.: KX0439740
AMEC Environment & Infrastructure 3456 Opie Crescent Prince George, BC, CANADA V2N 2P9	DATUM: NAD 83	2012 SUBSURFACE DEWATERING SYSTEM	REV NO.: A
	PROJECTION: UTM Zone 10		FIGURE 8
	SCALE: 1:7,500		

amec

This drawing was originally produced in colour.



Groundwater Decline (m)

	Groundwater Decline (m)
Yellow	0
Blue	0.5 - < 5
Green	≥ 5

West Quesnel Land Stability Program

CLIENT:	CITY OF QUESNEL
	AMEC Environment & Infrastructure 3456 Opie Crescent Prince George, BC, CANADA V2N 2P9
DWN BY:	BB
CHK'D BY:	DO
DATUM:	NAD 83
PROJECTION:	UTM Zone 10
SCALE:	1:7,500
TITLE:	GROUNDWATER DRAWDOWN 2012 SUBSURFACE DEWATERING SYSTEM
DATE:	NOVEMBER 2014
PROJECT NO.:	KX0439740
REV NO.:	A
	FIGURE 9

This drawing was originally produced in colour.

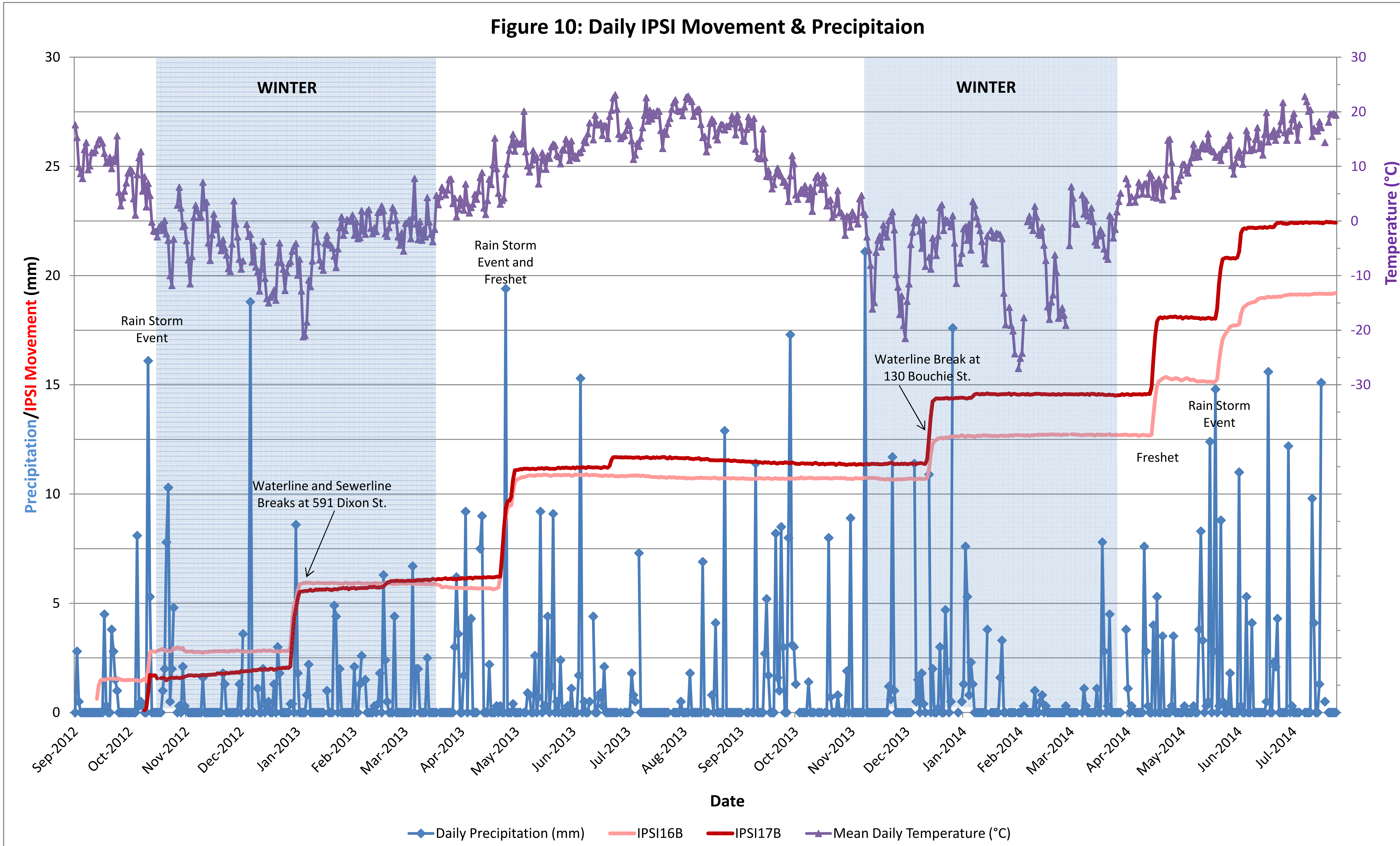


Figure 10: Daily IPSI Movement & Precipitaion
WINTER
WINTER
Rain Storm Event
Waterline and Sewerline Breaks at 591 Dixon St.
Rain Storm Event and Freshet
Waterline Break at 130 Bouchie St.
Rain Storm Event
Freshet
Precipitation/IPSI Movement (mm)
Temperature (°C)
Date
Sep-2012
Oct-2012
Nov-2012
Dec-2012
Jan-2013
Feb-2013
Mar-2013
Apr-2013
May-2013
Jun-2013
Jul-2013
Aug-2013
Sep-2013
Oct-2013
Nov-2013
Dec-2013
Jan-2014
Feb-2014
Mar-2014
Apr-2014
May-2014
Jun-2014
Jul-2014
0
5
10
15
20
25
30
-30
-20
-10
0
10
20
30
Daily Precipitation (mm)
IPSI16B
IPSI17B
Mean Daily Temperature (°C)