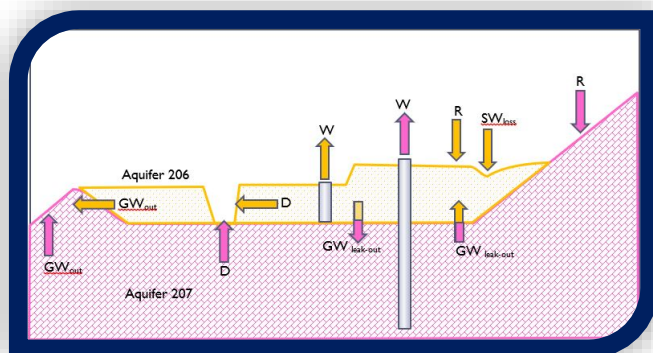


# Mill Bay Waterworks District: Local Aquifer Study

*Prepared for:*



**Mill Bay Waterworks District**  
**P.O. Box 58, 875 Deloume Rd.**  
**Mill Bay, BC**  
**V0R 2P0**



*Prepared by:*

**November, 2018**  
**Project: 16-076-02**

**Western Water Associates Ltd.**  
#301 – 1095 McKenzie Avenue  
Victoria, B.C. V8P 2L5 in association with:

**HYDRO•GEO•LOGIC**  
Professional Groundwater Consulting

Mike Wei, P. Eng. | 250-658-4828 | waterwei@telus.net

## Executive Summary – MBWD: Local Aquifer Study

Western Water Associates Ltd. (WWAL) was retained by Mill Bay Waterworks District (MBWD) to conduct a desktop study of the sand and gravel aquifer (Aquifer 206) and fractured bedrock aquifer (Aquifer 207) that supply water to the MBWD production wells. The overall goals of the study were to compile available information and to summarize areas of pumping stress to identify potential areas for further groundwater exploration and development.

WWAL compiled available pumping test reports and developed a spreadsheet database summarizing the key pumping test attributes (e.g., date of test, pumping rate, drawdown behaviour, etc.). The database comprised analyses from 25 pumping tests for 18 wells completed in Aquifers 206 and 207 (including all MBWD production wells and other wells). The summary of key attributes allowed pumping tests conducted over time for a specific well and between wells to be more systematically and objectively compared and contrasted.

Available groundwater levels from well records were also compiled and analyzed for both aquifers. This allowed WWAL to map overburden thickness and groundwater level elevations to describe groundwater flow directions and hydraulic gradients. Groundwater flow in both the overburden and underlying bedrock is from the upland area to the south (slopes of Mt. Wood) towards Shawnigan Creek (to the north) and Saanich Inlet (to the east). This upland area is inferred to be the main area of recharge for both aquifers. Recharge to Aquifer 206 occurs annually in the spring and averages about 0.36 m/year. Aquifer 207 recharge begins in late fall and peaks in the spring, with an average annual recharge of about 0.43 m/year. This relatively long period of recharge for Aquifer 207 seems unique and may reflect enhanced storage capacity of the bedrock aquifer. The groundwater levels also suggest vertical leakage occurs between Aquifers 206 and 207.

The transmissivity of Aquifer 206, based on available pumping tests, ranges from 1630 m<sup>2</sup>/day to 0.1 m<sup>2</sup>/day, with a geometric mean of 54 m<sup>2</sup>/day. Local watershed boundaries and groundwater elevations in the bedrock allowed WWAL to delineate a sub-area of Aquifer 207 to help MBWD focus its exploration, management and protection efforts with respect to the bedrock aquifer. Transmissivity of Aquifer 207 based on pumping tests range from 19 m<sup>2</sup>/day to 0.3 m<sup>2</sup>/day, with a geometric mean of 3 m<sup>2</sup>/day.

Pumping tests for MBWD wells 786, 21614 and 15603 (wells where concerns regarding decrease in reported capacity have been expressed by MBWD) were also reviewed to understand how these wells behaved when pumped. Well 786 is completed in sand and gravel (in Aquifer 206) within an incised bedrock channel. This well may therefore experience increasing rates of drawdown with pumping time because the aquifer thickness is spatially limited. The thicknesses of overburden and sand and gravel deposits within Aquifer 206 are variable. Anyone performing a pumping test of a well completed into thicker sand and gravel in this aquifer should be mindful of the possibility of thicker sections being bounded and how this impacts the rate of drawdown during the well's long-term operation.

For wells completed in fractured bedrock in the area (Aquifer 207), pumping was found to typically induce an initial period of linear flow, where the rate of drawdown increased gradually with time. This linear flow period can last up to one day or more. Radial flow, characteristic of an “ideal aquifer” where the rate of drawdown is constant, begins to dominate as pumping continues. Anyone performing a pumping test of a well completed in fractured bedrock should recognize this initial period of linear flow when assessing the long-term well yield. If not, aquifer transmissivity and well capacity could be over-estimated and interference impacts on neighbouring wells under-estimated. The capacity of bedrock well 15603 may also be limited by the drawdown to the depth of a water-bearing fracture reported at ~74 m. Pumping test data suggest that when drawdown drops to below ~74 m, the rate of drawdown in the well increases significantly. The 2016 and 2017 well capacity estimates for bedrock well 21614 were less than those originally calculated likely because of the lower static water level and saturated thickness (resulting in a decrease in available drawdown and transmissivity) in the 2016 and 2017 tests.

WWAL developed a map of drawdown in Aquifers 206 and 207 from operational pumping of MBWD’s production wells pumping at their individual capacities. The map shows drawdown (based on the Cooper-Jacob equation) is expected to occur mostly in the northern portion of the MBWD service area; pumping stress in the southern portion of the service area was inferred to be light. The study also reviewed the water budgets developed for Aquifers 206 and 207 in 2016 by SLR Consulting (Canada) Ltd. The water budget showed Aquifer 206 in various degrees of deficit for all three climate scenarios - average, dry and wet year. The ratio of expected withdraws to precipitation recharge for Aquifer 206 ranged from 42% to just over 100% for a wet to dry year, respectively. In contrast, the water budget for Aquifer 207 showed a slight deficit only during the dry year scenario. The ratio of expected withdraws to precipitation recharge for Aquifer 207 was estimated to be between 4% (wet year) to 11% (dry year). This suggests Aquifer 206 is more heavily used compared to its water supply potential than Aquifer 207.

This report provides a number of recommendations for MBWD’s consideration in relation to the supply of their production wells, as well as recommendations for potential additional work to explore for additional supply and for management of their source aquifers:

- Test the specific capacity of the MBWD production wells annually to check well performance on an on-going basis;
- Locate the original pumping test data for MBWD wells 1452 and 1453 to provide a baseline of well performance for these two wells;
- Measure and record quantities diverted from each MBWD production well to support aquifer yield and water budget assessments;
- Compile historical quantities and water levels from MBWD production wells into digital format;
- As standard practice, use diagnostic and derivative plots to help interpret pumping tests;
- Review available LIDAR data (from the CVRD) to check potential for enhanced porosity in the bedrock and conduct a lineament analysis to identify potential locations for drilling to explore for additional supply in the bedrock;
- Explore the feasibility of electromagnetic geophysical (EM) surveys to help target any future test drilling;

- Consider exploring for additional supplies in areas of thicker overburden (for Aquifer 206) and in areas outside of the expected pumping stress areas (both Aquifers 206 and 207);
- Consider installing an observation well in the southern part of the MBWD service area to better understand aquifer conditions in that area;
- Consider discussing with FLNR the benefits of registering a water allocation restriction for Aquifer 206 and developing water allocation plans for Aquifers 206 and 207 to provide an aquifer-wide context to guide future allocation of groundwater; and
- Continue to collaborate with ENV and FLNR to improve the water budgets for Aquifers 206 and 207.

November 2, 2018

Mill Bay Waterworks District  
PO Box 58, 875 Deloume Road  
Mill Bay, BC V0R 2P0

**Re: MBWD: Local Aquifer Study Report**

Western Water Associates Ltd. (WWAL) is pleased to provide this local aquifer study report of Aquifers 206 and 207 for the Mill Bay Waterworks District (MBWD).

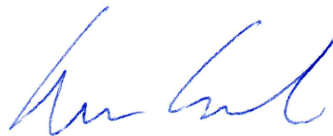
We trust that the professional opinions and advice presented in this document are sufficient for your current requirements. Should you have any questions, or if we can be of further assistance in this matter, please contact the undersigned.

The report was co-written by our senior groundwater consultant Mike Wei, P.Eng. of Hydro.Geo.Logic and Tim Sivak, G.I.T. of WWAL and reviewed by Chad Petersmeyer, P.Geo. and Doug Geller, P.Geo. of WWAL.

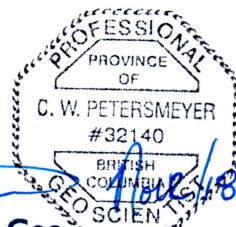
**WESTERN WATER ASSOCIATES LTD.**


**Mike Wei, MS. P.Eng**  
**Senior Hydrogeologist**



**Tim Sivak, B.Sc. G.I.T**  
**Geoscientist**

**Chad Petersmeyer, M.Sc., P.Geo**  
**Senior Hydrogeologist**

## TABLE OF CONTENTS

|                                                            |           |
|------------------------------------------------------------|-----------|
| <b>1. INTRODUCTION</b>                                     | <b>1</b>  |
| 1.1 PROJECT BACKGROUND                                     | 1         |
| 1.2 SCOPE OF SERVICES                                      | 2         |
| 1.3 PUMPING TEST DATABASE                                  | 2         |
| <b>2. SETTING</b>                                          | <b>4</b>  |
| 2.1 SITE DESCRIPTION                                       | 4         |
| 2.2 GEOLOGIC SETTING                                       | 4         |
| 2.2.1 SURFICIAL GEOLOGY                                    | 5         |
| 2.2.2 BEDROCK GEOLOGY                                      | 7         |
| 2.3 REGIONAL HYDROGEOLOGY                                  | 8         |
| 2.3.1 FLOW DIRECTIONS AND GRADIENTS                        | 8         |
| 2.3.2 RECHARGE                                             | 10        |
| <b>3. HYDRAULIC RESPONSE TO PUMPING</b>                    | <b>11</b> |
| 3.1 AQUIFER 206                                            | 11        |
| 3.1.1 WELL 786 (WTN 37733)                                 | 12        |
| 3.1.2 WELL 778 (WTN 84818)                                 | 14        |
| 3.1.3 WELL 783 (WTN 85108)                                 | 14        |
| 3.1.4 WELL 1452 (WTN 56015) AND WELL 1453 (WTN 56016)      | 14        |
| 3.2 AQUIFER 207                                            | 14        |
| 3.2.1 WELL 1387 (WTN 85151)                                | 15        |
| 3.2.2 WELL 21614 (WTN 88224)                               | 15        |
| 3.2.3 WELL 15603 (WTN 89731)                               | 17        |
| <b>4. AREAS OF PUMPING STRESS</b>                          | <b>19</b> |
| <b>5. CONCEPTUAL MODEL OF AQUIFERS 206 AND 207</b>         | <b>22</b> |
| 5.1 INFLOW OF WATER TO THE AQUIFERS                        | 23        |
| 5.1.1 PRECIPITATION RECHARGE                               | 23        |
| 5.1.2 INFLOW FROM STREAM LOSSES                            | 24        |
| 5.1.3 LEAKAGE BETWEEN AQUIFERS 206 AND 207                 | 24        |
| 5.2 OUTFLOW OF WATER FROM THE AQUIFERS                     | 24        |
| 5.2.1 OUTFLOW OF GROUNDWATER DISCHARGE TO STREAMS, SPRINGS | 25        |
| 5.2.2 GROUNDWATER OUTFLOW                                  | 25        |
| 5.2.3 WELL PUMPING                                         | 25        |
| 5.3 CHANGE IN WATER STORAGE                                | 25        |
| 5.4 WATER BUDGETS FOR AQUIFERS 206 AND 207                 | 26        |
| 5.4.1 ANNUAL WATER BUDGET FOR AQUIFERS 206 AND 207         | 26        |
| 5.4.2 UNCERTAINTIES WITH WATER BUDGETS                     | 27        |
| <b>6. IMPLICATIONS FOR FUTURE GROUNDWATER DEVELOPMENT</b>  | <b>28</b> |
| <b>7. RECOMMENDATIONS</b>                                  | <b>28</b> |
| 7.1 ANNUAL TESTING TO MONITOR WELL PERFORMANCE             | 28        |
| 7.2 PUMPING TEST INFORMATION FOR WELLS 1452 AND 1453       | 29        |
| 7.3 MEASURE AND RECORD QUANTITIES DIVERTED FROM EACH WELL  | 29        |

|            |                                                                              |           |
|------------|------------------------------------------------------------------------------|-----------|
| 7.4        | COMPILE WATER QUANTITY AND WATER LEVEL DATA FOR THE MBWD PRODUCTION WELLS .. | 29        |
| 7.5        | DIAGNOSTIC AND DERIVATIVE PLOTS TO HELP INTERPRET PUMPING TESTS .....        | 29        |
| 7.6        | REVIEW OF LIDAR DATA AND LINEAMENT ANALYSIS .....                            | 30        |
| 7.7        | REMOTE SENSING TO INFORM DRILLING.....                                       | 30        |
| 7.8        | ADDITIONAL OBSERVATION WELLS .....                                           | 31        |
| 7.9        | GROUNDWATER EXPLORATION .....                                                | 31        |
| 7.10       | WATER ALLOCATION PLANNING AND WATER ALLOCATION RESTRICTIONS .....            | 31        |
| 7.11       | COLLABORATE TO IMPROVE THE WATER BUDGETS FOR AQUIFERS 206 AND 207 .....      | 32        |
| <b>8.</b>  | <b>ACKNOWLEDGEMENTS .....</b>                                                | <b>32</b> |
| <b>9.</b>  | <b>REFERENCES .....</b>                                                      | <b>33</b> |
| <b>10.</b> | <b>GLOSSARY .....</b>                                                        | <b>36</b> |

## List of Figures

|             |                                                                                                                                                                                                                                                                                                                             |    |
|-------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 2.1  | Groundwater level hydrograph from Observation Well 350 completed in Aquifer 206. The seasonal recharge period for Aquifer 206 is depicted by the horizontal dashed lines. Monitoring was initially done by the land owner (1989-1992) and later by ENV (2001-2007). The well (WTN 81555) has since been decommissioned..... | 10 |
| Figure 2.2. | Groundwater level hydrograph from Observation Well 380 completed in Aquifer 207. The seasonal recharge period for Aquifer 207 is depicted by the horizontal dashed lines. ....                                                                                                                                              | 11 |
| Figure 5.1. | Schematic diagram of Aquifers 206 and 207 and the major water inflow and outflow processes. ....                                                                                                                                                                                                                            | 23 |

## List of Maps (following text)

|         |                                                         |
|---------|---------------------------------------------------------|
| Map 1.  | Estimated Overburden Thickness                          |
| Map 2a. | Reported Groundwater Level Elevation in Overburden      |
| Map 2b. | Reported Groundwater Level Elevation in Bedrock         |
| Map 3.  | Vertical Groundwater Flow Gradient                      |
| Map 4a. | Radius of Influence (ROI) for MBWD Wells in Aquifer 206 |
| Map 4b. | Radius of Influence (ROI) for MBWD Wells in Aquifer 207 |

## List of Tables

|            |                                                                                                                                                                                          |    |
|------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Table 1.1. | Correlation of available reports to wells in the MBWD area. Note: MBWD production wells in bold. Wells completed into Aquifers 206 and 207 are shaded yellow and pink, respectively..... | 3  |
| Table 3.1. | Comparison of aquifer hydraulic properties calculated from pumping tests of bedrock wells in the MBWD area. N/C = not calculated; SWL = Static water level; S = Storativity.....         | 18 |

---

|                                                                                                                                                                           |    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Table 4.1. Pumping rates used to calculate drawdown in Aquifers 206 and 207 caused by pumping of the MBWD production wells.....                                           | 20 |
| Table 4.2. Summary of aquifer hydraulic parameters (transmissivity and storativity) for Aquifers 206 and 207 (note storativity values are lacking for both aquifers)..... | 21 |
| Table 5.1. Indicator of annual well pumping to precipitation recharge for Aquifers 206 and 207.....                                                                       | 27 |
| Table 7.1. Example of how quantity diverted can be recorded.....                                                                                                          | 29 |
| Table 7.2. Conductance of some common hydrogeological conditions.....                                                                                                     | 30 |

## I. INTRODUCTION

At the request of Mill Bay Waterworks District (MBWD), Western Water Associates Ltd. (WWAL) has completed a local aquifer study for the MBWD service area. Prepared with the assistance of Mike Wei, P.Eng. (HydroGeoLogic), this report presents the results of this study and provides recommendations for future work.

### I.1 Project Background

There are three aquifers mapped by the Province of British Columbia that underlie the MBWD service area:

- Aquifer 206 (Mill Bay): An aquifer comprising surficial sand and gravel deposits underlying the majority of MBWD service area.
- Aquifer 204 (Cobble Hill): A fractured bedrock aquifer underlying a portion of the MBWD service area north of Shawnigan Creek.
- Aquifer 207 (Bamberton): A bedrock aquifer underlying all of the MBWD service area (beneath Aquifer 206, where present), except north of Shawnigan Creek where Aquifer 204 is mapped.

In response to a suspected decline in yields for MBWD supply wells completed in Aquifers 206 and 207, historical water level and flow data for the wells were previously compiled and assessed (Thurber, 2016a). The assessment compared the long-term operational capacities of the wells to the previously estimated long-term yields. It was found that the wells were being operated at long-term average rates of between 7% and 31% of the initial estimated yields. The pumping water levels in some of the supply wells appeared to be approaching the tops of the pumps during the dry season.

To further investigate the possible causes of differing long-term operational rates and initial estimated yields for the MBWD wells, rehabilitation and test pumping of overburden well 786 and test pumping of bedrock wells 1387, 15603, and 21614 were respectively completed in the Spring and Fall of 2016 by the MBWD under the direction of Chad Petersmeyer, P.Geo, (previously with Thurber Engineering Ltd., and with WWAL since 2016). The results of this test pumping program appeared to confirm the interpretation from the compiled historical operational data, further indicating that the wells were not capable of producing at their rated capacities during the dry season. The main cause of the reduced yields was believed to be lower local and/or regional groundwater levels in the respective aquifers (Aquifers 206 and 207).

Groundwater in the area is recharged primarily from rainwater, and with increased development and climate change, there are concerns about the sustainability of the groundwater resource in the area. MBWD is seeking to improve the understanding of water resources within the MBWD service area, in particular a better knowledge of the hydrologic cycle, available water quantity, flow system, water demand, and factors affecting sustainability. It is our understanding that MBWD intends to use this information to identify areas where groundwater supply may be stressed and to look for areas to focus for future groundwater development.

## **I.2 Scope of Services**

The main components of the work completed as part of this study include:

- Compiled and organized existing information provided by MBWD, from our archives, and from various other public and private sources.
- Reviewed the compiled information to build on the conceptual understanding of the aquifers.
- Summarized the available water budgets for Aquifers 206 and 207 and the relevance to MBWD, and
- Reported on findings and presented recommendations for future work.

This study focused mainly on Aquifers 206 and 207. While the study area includes Aquifer 204, that aquifer only occupies a tiny northern portion of the MBWD service area north of Shawnigan Creek. The aquifer boundary along Shawnigan Creek separating Aquifers 204 and 207 was based on a stream feature and not on geological differences. Geological attributes of Aquifer 204 within the MBWD service area are assumed to be similar to Aquifer 207.

## **I.3 Pumping Test Database**

WWAL compiled a pumping test database for wells located within the MBWD service area. The database contains a summary of hydrogeological data from MBWD production wells and other pumping wells completed in Aquifers 206 and 207. The database was constructed by reviewing hydrogeological studies previously completed by WWAL and Thurber, and from other sources provided by MBWD. The objective of the pumping test database is to facilitate understanding the complex hydrogeological conditions and characteristics of Aquifers 206 and 207. A summary of the data compilation for the wells is depicted in Table I.1. Map I shows the wells discussed in this report.

| Report                                                                                                                                                                               | Well name: |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       | Reference report | in                |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|-------|---------|-------|-------|-------|-------|-------|-------|------|--------|-------|-------|-------|-------|-------|-------|-------|-------|------------------|-------------------|
|                                                                                                                                                                                      | 76-2       | 786   | Garnett | 80-2  | OW380 | 81-5  | 785   | 92-1  | 778   | 93-1 | 94-1   | 15603 | 1387  | 1386  | 21614 | 13286 | 42776 | 1452  | 1453  |                  |                   |
| Well tag number (WTN):                                                                                                                                                               | 94356      | 37733 | 39625   | 46804 | 46810 | 94363 | 85199 | 88357 | 84818 | -    | 101819 | 89731 | 85151 | 85275 | 88224 | 69141 | -     | 56015 | 56016 | 85108            |                   |
| Terracon Geotechnique Ltd., Alpex – Mill Bay Production Wells: February 1994 Summary Report, Report for Mill Bay Waterworks District, 1994.                                          |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | TGL (1994)        |
| Livingston Associates Ltd., Groundwater Exploration Program, Report for Mill Bay Waterworks District, August 26, 1977.                                                               |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | ELA (1977)        |
| Thurber Engineering Ltd., Well 786 Rehabilitation Summary, Report for Mill Bay Waterworks District, March 3, 2016.                                                                   |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | TEL (2016)        |
| Ministry of Environment, Compendium of Re-evaluated Pumping Tests in the Cowichan Valley Regional District, Vancouver Island, British Columbia, 2014.                                |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | Carmichael (2014) |
| Thurber Engineering Ltd., TH87-1 (Well #785) Assessment Report. Report for Mill Bay Waterworks District. 2010.                                                                       |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | TEL (2010)        |
| Lowen Hydrogeology Consulting Ltd., Well 06-1 Report for Water Source Approval, Report for 687033 BC Ltd. Fraser McColl and Gerald Hartwig, 2006.                                    |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | LHC (2006)        |
| Lowen Hydrogeology Consulting Ltd., Mill Bay Waterworks District Well 2004-01. Report to Mill Bay Waterworks District, January, 2005.                                                |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | LHC (2005)        |
| Lowen Hydrogeology Consulting Ltd., Re-assessment of MBWD well 1387 capacity considering Mill Springs well 21614 drawdown interference, Mill Bay, BC. Report to 687033 BC Ltd, 2009. |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | LHC (2009)        |
| Lowen Hydrogeology Consulting Ltd., Well Drilling and Capacity Testing for the Deloume Road Subdivision, Report to 613711 B.C. Ltd., 2003.                                           |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | LHC (2003)        |
| Lowen Hydrogeology Consulting Ltd., Well 07-01 Report for Water Source Approval, Report for 687033 BC Ltd. Fraser McColl and Gerald Hartwig, 2007.                                   |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | LHC (2007)        |
| Lowen Hydrogeology Consulting Ltd., Mill Springs Subdivision – Well 21614. Report for Gerald Hartwig 2010.                                                                           |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | LHC (2010)        |
| Western Water Associates Ltd., MBWD 2016 Supply Well Test Pumping Program Results, Report for Mill Bay Waterworks District, 2016.                                                    |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | WWAL (2017b)      |
| Western Water Associates Ltd., Well 21614 Rehabilitation and 2017 Test Pumping Results. Report to Mill Bay Waterworks District, November 15, 2017.                                   |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | WWAL (2017c)      |
| Western Water Associates Ltd. Well Assessment: Mill Bay Waterworks District Deer Park Supply Well (WIN 13286). Report to Mill Bay Waterworks District. 2017.                         |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | WWAL (2017a)      |
| Hodge Hydrogeology Consulting, Mill Bay Waterworks District New Well 783. Report to Mill Bay Waterworks District. April, 2006.                                                       |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | HHC (2006)        |
| Lowen Hydrogeology Consulting, Letter to Mill Bay Waterworks District. March 10, 2017.                                                                                               |            |       |         |       |       |       |       |       |       |      |        |       |       |       |       |       |       |       |       |                  | LHC (2017)        |

Legend

Aquifer 206

Aquifer 207

**Table I.1. Correlation of available reports to wells in the MBWD area. Note: MBWD production wells in bold. Wells completed into Aquifers 206 and 207 are shaded yellow and pink, respectively.**

WWAL organized the data in GIS framework to depict the hydrogeological data spatially. The following digital datasets were also compiled for this study:

- Digital bedrock geology mapping compiled by Cui et al. (2017).
- Aquifer Mapping from the BC Aquifer Classification System retrieved in April 2018,
- Groundwater wells data retrieved from the Province of British Columbia's GWELLS Database (2018),
- Digital Elevation Model (approximately 30 m resolution) from GeoGratis (2018),
- Satellite imagery downloaded from Google Satellite and Bing Satellite dated 2018,
- Watershed boundaries downloaded from BC Freshwater Atlas in April 2018, and
- Terrain Resource Inventory Mapping (TRIM) contours downloaded from DataBC in May 2018.

## 2. SETTING

### 2.1 Site Description

MBWD service area occupies an approximate area of 532 hectares and is situated within the Nanaimo Lowland physiographic region on the southeast side of Vancouver Island. Mill Bay is located about 29 km northwest of Victoria, BC and 19 km southeast of Duncan, BC. The area is reached by car by Highway 1 from the north and south, and Shawnigan Lake Road from the west.

WWAL delineated the study area (black outline on Map 1) using topographic contours and watershed boundaries to capture data points near the MBWD service area boundary for use in this study. MBWD service area is located completely within the study area. The MBWD service area has a northeast facing aspect, and its elevation ranges from 0 m (sea level) to about 220 m above sea level on an unnamed hill in the southern part of the study area. The area consists primarily of rural development, with light commercial development near Highway 1.

The closest surface water bodies are Shawnigan Lake approximately 5 km to the west, and Saanich Inlet which is adjacent to Mill Bay to the east. The creeks in the service area include Handysen Creek, Hollings Creek and Shawnigan Creek which ultimately drain into Saanich Inlet, as well as minor creeks flowing east of Highway 1 to Saanich Inlet.

Victoria International Airport Climate Station (Climate ID: 1018620) climate normals (1981 to 2010) show average total annual precipitation of 882.9 mm, and average monthly temperatures ranging between 4.0°C and 16.8°C. Victoria International Airport is located on Saanich Peninsula about 10 km east of Mill Bay.

### 2.2 Geologic Setting

The geologic setting of MBWD service area is important because it helps us understand conceptually where groundwater in the area occurs and the supply potential for MBWD. By understanding the surficial and bedrock geology, we can identify areas where further groundwater exploration could be considered, and areas where exploration is less favourable.

Surficial geologic deposits comprise Aquifer 206, and the bedrock comprises Aquifer 207. MBWD has production wells currently pumping from both aquifers. The following sub-sections describe the surficial and bedrock geology of the area and discuss where groundwater in the area occurs and the potential for further exploration.

### 2.2.1 Surficial Geology

Aquifer 206 underlies the MBWD. The aquifer, as currently mapped by the Province of BC, is bounded to the north by Shawnigan Creek and to the west near Handysen Creek and covers an area of about 2.6 km<sup>2</sup>. The southern boundary is an upland area that has been delineated based on area of aquifer development but may extend further (i.e., towards the marsh at the headwaters of Handysen Creek). The eastern extent of the aquifer is approximately 50 to 300 m from Saanich Inlet, where the unconsolidated sediments thin out. Aquifer 206 is likely recharged from percolation of precipitation, infiltration from surface water bodies over the aquifer, and (in some areas) upward vertical leakage from Aquifer 207. Recharge to Aquifer 206 is discussed in further detail in sections 2.3.1 (Flow Directions and Gradients) and 2.3.2 (Recharge) of the report.

VWAL compiled and reviewed well records from GWELLS and information from groundwater investigations from our archives, and geological cross sections provided by the BC Ministry of Environment and Climate Change Strategy (ENV) (Rathfelder, 2018; pers. comm.). The surficial geology has been summarized by SLR (2017), Blythe et al., (1993), and Halstead (1965). This section briefly describes the surficial geology at specific areas within the MBWD service area and is based on the mapping compiled from the above sources, as well as well records from GWELLS, with particular focus on opportunities for exploring for additional groundwater supply.

The surficial geology in the Mill Bay area, including Aquifer 206, is interpreted as mixtures of glaciofluvial and till-like deposits, and marine deposits from the waning stage of the last period of glaciation (10,000 to 14,000 years ago). Halstead (1965) mapped the area as glaciofluvial deposits consisting of hummocky, kettled, kame deposits of sand and gravel, marine/glaciomarine deposits consisting of silt, clay, stony clay and till-like mixtures, and moraine deposits consisting of till, lenses of gravel, sand and silt. Coarse-textured kettle and kame units were deposited by down-wasting glaciers. Fine-textured marine sediments containing ice-rafted materials were deposited in layers of variable thickness overlying older unconsolidated deposits (if present) below an elevation of about 80 m.

Blythe et al. (1993) described the area as comprising primarily of a hummocky morainal blanket (>1 m thick) overlying bedrock. The term “morainal” is used to describe overburden deposited directly by glaciers, composed of well-packed material with variable texture. In the north, the morainal deposit overlies a glaciofluvial deposit of unknown thickness. The mapping also depicts shallow bedrock under a veneer (<1 m) of overburden on an unnamed hill approximately 5 km east of Baldy Mountain and outside the MBWD service area.

SLR (2017) summarized the overburden deposits as interbedded glaciofluvial and morainal deposits of variable thickness and areal extent. Overburden deposit thicknesses are structurally controlled by the nature of the bedrock surface. “Overburden” is a general term used to describe all unconsolidated deposits, from coarse-grained materials such as gravels and sands, to fine-grained material such as silts

and clays, or even hard, mixed materials like till, which is very common in glaciated areas. The glaciofluvial units are typically between 5 m and 15 m thick, unless bound within bedrock channels where overburden deposit thicknesses can be up to 30 m thick.

The variability in surficial materials, their thicknesses, and areal coverage make it challenging to map out discrete units for groundwater supply potential. However, thicker overburden deposits imply greater potential for groundwater supply, as they have a greater saturated thickness, and potentially larger aquifer volumes for storing water. WWAL estimated the thickness of overburden in the MBWD area from bedrock and maximum drilling depths provided in water well logs from the GWELLS database. A multilevel B-Spline interpolation method (Lee and Shin, 1997) was used in GIS to estimate overburden thickness between well points. Map I, following the text, shows the inferred overburden thickness for the study area. The overburden thicknesses depicted are estimates based on the data available. Overburden thickness is better constrained in areas of higher well density and more uncertain in areas of lower well density.

Overburden thickness is variable throughout MBWD service area, and ranges up to about 70 m thick, with an average thickness of about 16 m. Darker colours in Map I represent thicker overburden and lighter colours represent thinner overburden. WWAL cross-referenced the overburden thickness derived from GIS with well logs and cross-sections provided by ENV (Rathfelder, 2018 pers. comm.).

Locations within MBWD service area with thicker overburden deposits are described below as areas A through C and are depicted in Map I. These areas are described as follows:

#### Area A – Mill Springs:

The surficial geology of Mill Springs consists of thicker sand and gravel deposits overlying bedrock. Material descriptions from driller logs are consistent with glaciofluvial and marine / glaciomarine geologic units from Halstead (1965). While Map I shows overburden thickness in this area can reach over 70 m, only well with well tag number (WTN) 80040, encountered weathered bedrock at 76 m depth.

MBWD production well 778 is located in Mill Springs and is 32.3 m deep, completed in gravel. The stratigraphy consists of 36 m of interbedded silts, sands and gravel units separated by a confining layer of clay. Deer Park well (13286) is also in the general area and is 18 m deep, completed in silty sand and gravel underneath a 5 m thick confining clay layer.

#### Area B – Wheelbarrow Springs:

Map I depicts overburden thickness in this area as being between about 10 and 25 m thick. Wei (1987) described the overburden as comprising of unconfined sand and gravel overlying till and bedrock in a sequence up to about 30 m thick. There was a gravel pit located on the top of the hill where gravel was formerly extracted. As some of the well logs in this area contain drilling information from prior to the gravel mining operation, the current thickness of overburden in this area may be less than that shown in Map I. Springs have been observed along the edge of the slope that exists at about 60 m elevation north of Pratt Road and continuing along Lodgepole Road, as these areas are often marshy or wet even during dry times of year.

The gentle sloped area near the sports field along Deloume Road consists of a sequence of interbedded sands, silts and clays overlying sand and gravel. This stratigraphy suggests the lower sand and gravel may be partially confined. From well logs and sections, overburden is up to approximately 35 m thick, which is thicker than elsewhere in Area B. The presence of an east-west trending bedrock channel, targeted by ELA (1977) and into which Well 786 is completed, is further described in Section 3.1.1 (Well 786 (WTN 37733)) below.

MBWD production wells 783, 786, 1452 and 1453 are located in the Wheelbarrow Springs area. Wells 783, 1452 and 1453 are completed to depths between 8.1 and 9.8 m within the surficial sand and gravel, and Well 786 is completed to a depth from surface of 37.8 m in a lower sand and gravel, which underlies less-permeable sediments.

#### Area C – Foreshore:

Map 1 shows the overburden thickness east of Highway 1 is between approximately 10 m and 25 m. From logs of wells drilled in the area retrieved from ENV's GWELLS database, drillers describe the material as silty gravel, hardpan, and silty blue clay. Cross-sections provided by ENV (Rathfelder, 2018) show wells located east of Highway 1 drilled through predominantly marine clays overlying bedrock and underlying a blanket of sands and gravels located near the ground surface, whereas the wells located west of Highway 1 (e.g., Wheelbarrow Springs, Mill Springs, etc.) are in predominantly glaciofluvial sediments and/or tills overlying bedrock, or fine-textured layers of variable thickness overlying older unconsolidated deposits. There are no MBWD production wells currently located in the foreshore area.

Map 1 also depicts areas where overburden is thin. Thinner overburden suggests a lower potential for groundwater supply in Aquifer 206. In areas where overburden thins, most water wells are completed in bedrock (Aquifer 207). Data coverage in the north and southeast portions of the study area is poor, and the conceptual understanding of overburden hydrogeology may be improved with additional data points from wells that have not been included in GWELLS, or from other sources.

### **2.2.2 Bedrock Geology**

Aquifer 207 underlies Aquifer 206 in the MBWD service area. MBWD Production wells 21614, 1386, 1387 and 15603 are completed in Aquifer 207. They are located at Mill Springs and Wheelbarrow Springs in the MBWD service area.

According to ENV (1996), the aquifer is bound to the north by Shawnigan Creek and covers an area of about 25.1 km<sup>2</sup>. The southern boundary extends to Bamberton Park and is delineated based on well development and bedrock mapping. The western extent of the aquifer is located east of the Shawnigan Lake watershed boundary. The eastern extent of the aquifer is Saanich Inlet.

The bedrock geologic units and major geologic features within the MBWD service area were compiled from Cui et al. (2017) and Muller (1977). Aquifer 207 is comprised primarily of Early Jurassic to Middle Jurassic granodioritic intrusive rocks of the Island Plutonic Suite. Older volcanic rocks of the Bonanza Group underlie the southern edge of the service area (Cui et al., 2017).

Older sedimentary rocks of the Quatsino Formation are also mapped approximately 5 km southwest of MBWD service area. This unit is composed of limestone, marble and calcareous sedimentary rocks (Massey et al., 1994). Karst features may be present within or near the service area either as epikarst, sinkholes, or caves. Karst arises from dissolution of carbonate rocks primarily at the soil-water interface and can have enhanced porosity relative to surrounding rocks (Freeze & Cherry, 1979). Enhanced porosity can provide greater capacity for bedrock to store more water and can also dampen or “slow” down a bedrock aquifer’s response to hydraulic changes (for example, during pumping - see further discussion in section 5.1.1 (Precipitation Recharge)). An exhaustive search for additional information on karst features in the area is beyond the scope of the current study.

The bedrock underlying MBWD service area is primarily composed of crystalline intrusive rocks, as described above, where groundwater is typically stored and flows within fractures and faults because primary porosity of these types of rocks is typically very low (<1%). Successful wells in a fractured bedrock aquifer such as Aquifer 207 encounter sufficient flows in water-bearing fractures (or faults) at depths that provide sufficient available drawdown. Usually, the yield of bedrock wells is lower than that of overburden wells. The lower transmissivity of bedrock formations (and lower specific capacity) means a greater amount of drawdown is required in bedrock wells to produce a given quantity of water.

The capacity of wells completed in Aquifer 207 depends on the characteristics of local fracturing (e.g., fracture depth, width, and persistence). Freeze & Cherry (1979) suggest that well yields for bedrock wells can also be related to topography, where bedrock wells located on top of hills may have lower yields, and bedrock wells located on valley floors may have greater yields. Fracture characteristics are often specific to a given location and can vary between wells drilled even short distances apart. Freeze & Cherry (1979) also note that a diminished well yield is generally observed with depth in crystalline aquifers.

## **2.3 Regional Hydrogeology**

### **2.3.1 Flow Directions and Gradients**

#### Horizontal Hydraulic Gradient:

WWAL constructed groundwater level elevation maps to depict horizontal groundwater flow in Aquifers 206 and 207 (see Maps 2a and 2b, respectively). Groundwater level elevation contours were constructed by grouping wells from the GWELLS database into those that were completed into overburden (Aquifer 206) and those completed into bedrock (Aquifer 207). The ground surface elevation value from a digital elevation model (DEM) was then extracted for each well location. The DEM is approximately 30 m resolution and is expressed relative to mean sea level. The groundwater elevation at each well location was calculated by subtracting the reported static water depth in the well from the DEM ground elevation. Groundwater elevations were contoured based on the values at individual well locations. Groundwater elevation contours are depicted in white for overburden (Map 2a) and magenta for bedrock (Map 2b). Horizontal hydraulic gradient was calculated from the change in hydraulic head over a given horizontal distance. On maps having the same interval between contours,

groundwater contours that are closely spaced reflect a steeper hydraulic gradient, and those that are widely spaced reflect a gentler hydraulic gradient.

Horizontal hydraulic gradients have similar flow directions in overburden and bedrock and appear to generally conform to topography. In the southern portion of the study area, the horizontal groundwater flow direction in overburden is northward towards Shawnigan Creek, and then to the east towards Saanich Inlet. In the north, groundwater flows horizontally southward towards Shawnigan Creek. Horizontal hydraulic gradient was not estimated in areas where there is poor data coverage.

Estimated horizontal hydraulic gradients in overburden (Map 2a) range between 0.03 and 0.1. Areas with steeper topography can have greater hydraulic gradients of up to 0.1, for example in the sloped area south of Aquifer 206. Flatter areas have gentler horizontal hydraulic gradients of approximately 0.03 or 0.04. There are insufficient wells located in the north and south east areas of MBWD service area to determine horizontal flow in overburden.

The hydraulic head plot for Aquifer 207 (Map 2b) supports the use of local watershed boundaries to delineate a sub-area of Aquifer 207 of most relevance to MBWD coinciding with local groundwater flow divides. Estimated horizontal hydraulic gradients in bedrock are greatest where there is high topographic relief and slope. In the area in the southwest corner of the study area, horizontal hydraulic gradient is between about 0.1 and 0.2. Note, however, that the gradient there is heavily influenced by only a few wells. The horizontal flow gradient in bedrock is more gradual downgradient to the north, ranging between about 0.03 and 0.09.

#### Vertical Hydraulic Gradient:

Relative vertical hydraulic gradient direction between overburden and bedrock within the MBWD service area is depicted in Map 3. Map 3 was created by noting the difference between the groundwater level elevation values in the overburden aquifer versus in the bedrock aquifer. The groundwater level elevations between well points are interpolated using a multilevel B-Spline interpolation method in GIS. Map 3 displays zones of upward gradient in green, and downward gradient in yellow. While the direction of vertical gradient can be mapped in Map 3, the magnitude of the vertical gradient cannot be quantified. This is because bedrock wells are typically open hole, and therefore open to water-bearing fractures at multiple depths and those depths are hard to predict from one location to the next.

Upward groundwater flow is inferred to occur in areas where the static water level elevation in bedrock is greater than the static water level elevation in overburden (green areas) and vice versa for downward groundwater flow (yellow areas). The arrows in Map 3 depict relative direction of vertical groundwater flow. Areas with upward flow are represented with green arrows, and those with downward flow are represented with red arrows. Areas where vertical gradient is negligible are represented by a blue equals sign. Areas where there are no wells completed in overburden are not included in the model and are classified as zones with poor data coverage. From Map 3, leakage from the underlying bedrock upward to the overburden is inferred to occur in upland areas in the southwest and eastern part of Aquifer 206. Leakage downward to bedrock from the overburden is interpreted to occur in the north and southeast areas of Aquifer 206.

### 2.3.2 Recharge

As noted above, recharge to Aquifers 206 and 207 comes from infiltration of winter season precipitation. Groundwater levels monitored in Provincial Observation Wells 350 (WTN 81555) and 380 (WTN 46810) drilled into Aquifers 206 and 207, respectively, show the recharge to both aquifers occurs seasonally in the spring (see Figures 2.1 and 2.2 below). There are differences in the rate and duration of recharge to the aquifers and for further discussion on this, please refer to Section 5 (Conceptual Model of Aquifers 206 and 207).

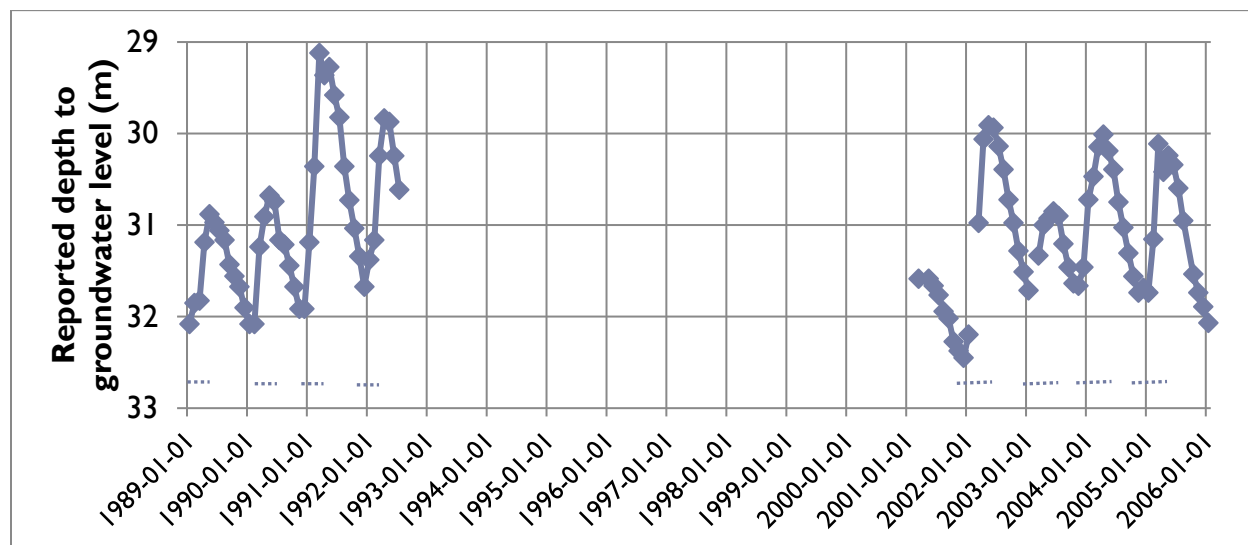


**Figure 2.1 Groundwater level hydrograph from Observation Well 350 completed in Aquifer 206. The seasonal recharge period for Aquifer 206 is depicted by the horizontal dashed lines. Monitoring was initially done by the land owner (1989-1992) and later by ENV (2001-2007). The well (WTN 81555) has since been decommissioned.**

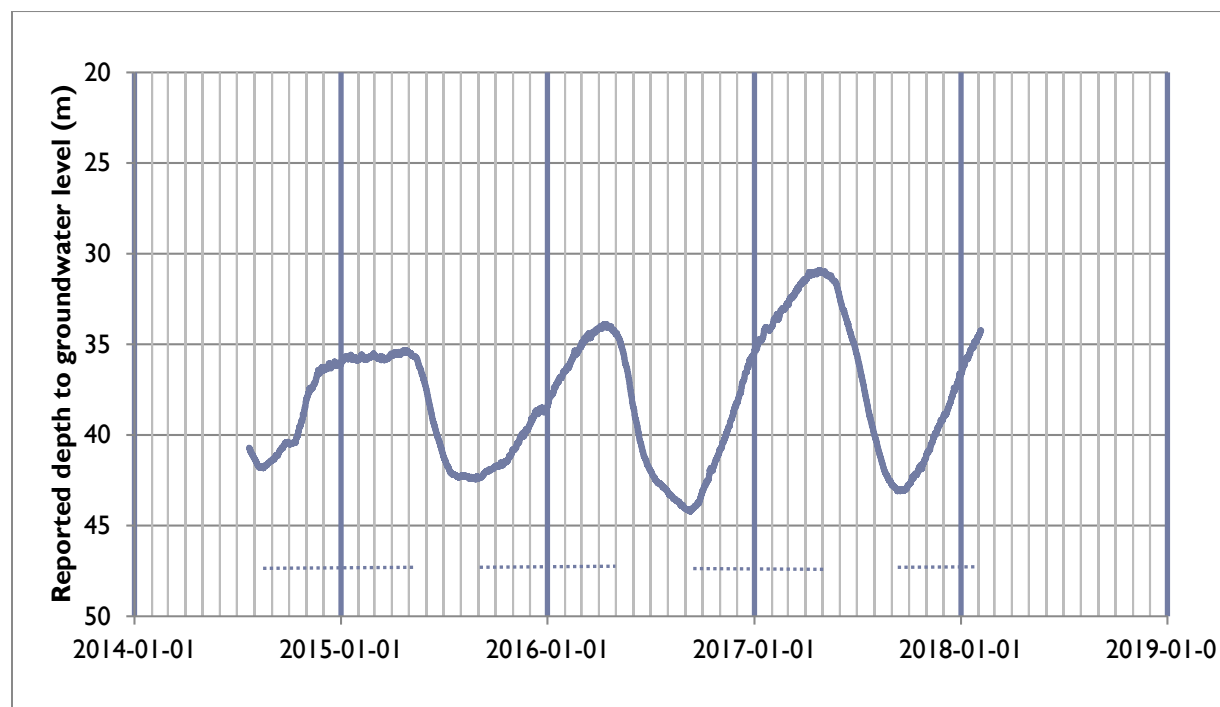


**Figure 2.2. Groundwater level hydrograph from Observation Well 380 completed in Aquifer 207. The seasonal recharge period for Aquifer 207 is depicted by the horizontal dashed lines.**

### 3. HYDRAULIC RESPONSE TO PUMPING

#### 3.1 Aquifer 206

Understanding an aquifer's response to well pumping provides valuable insight on the aquifer-for example on what may be limiting its yield and what its capacity is for further development. In this study 14 pumping tests were compiled from available reports for 12 different wells drilled into Aquifer 206, including MBWD production wells 786, 778, 783, 1452 and 1453 (see Table 1.1). Pumping tests for two wells, 786 and 785 (not currently a MBWD production well), were reviewed in detail to better understand aquifer behaviour in response to pumping. In general, the following observations were made:

1. Despite the wells being drilled into the same aquifer (e.g., Aquifer 206), the long-term pumping behaviour from well to well can be different and is very much influenced by the local geology: the lithology encountered during drilling, boundary locations within the aquifer, the available drawdown and the transmissivity of the aquifer materials.
2. It is important to have an idea of the geological context when analyzing pumping tests and predicting long-term pumping behaviour. Some wells, like well 785, showed pumping behaviour like an "ideal" aquifer (one in which pumping water level draws down at a rate that reflects radial flow to the well). Other wells, (e.g., well 786), behave more like they are pumping within a bounded aquifer.
3. Pumping test data were not available for two of the five MBWD production wells drilled into Aquifer 206 (wells 1452 and 1453). Without these data, it is not possible to compare well performance over time, unless the wells are retested to obtain the baseline information.

Specific comments for each MBWD production well are presented below.

### **3.1.1 Well 786 (WTN 37733)**

Well 786 was drilled into thicker (>35 m thick) unconsolidated sediments infilling a bedrock channel. Based on test drilling by ELA in 1977, the bedrock channel appears to run roughly east-west and is only a few tens of metres wide. The length of the channel is not known. The effect of this channel on pumping drawdown of well 786 is evident in Figure 3.1. The slope of drawdown during the test increased continuously up to 500 minutes, after which the pumping rate was reduced (Figure 3.1). This drawdown behaviour can be reproduced by using image well theory to mimic the effect of the bedrock channel boundaries when well 786 is pumped. The black line in Figure 3.1 is modelled from the image wells configured in Figure 3.2.

If the channel is further bounded along its length to the west or east (Figure 3.2 shows the channel bounded to the west for illustration purposes), the rate of drawdown would continue to increase with pumping time but this may not have been observable from the 1977 test because the test may not have been run long enough.

The re-development and re-test of well 786 in 2016 show that the static water level has declined significantly compared to test conditions in 1977. The static water level in February of 2016 was reported to be ~20m (TEL, 2016) below ground and 13.56 m below ground in August 1977, a drop of 6.5 m. The suspected decline in long-term capacity of well 786 may be explained by the limited aquifer extent resulting in a greater rate of drawdown in the well beyond what could be observed from a 1-day pumping test and a decrease in available drawdown due to decline in the static water level over the years. The drop in water level also effectively reduced the aquifer transmissivity. The Garnett (WTN 39625) well is likely drilled into the same bedrock channel ~250 m west of well 786, so a similar long-term pumping behaviour can be expected.

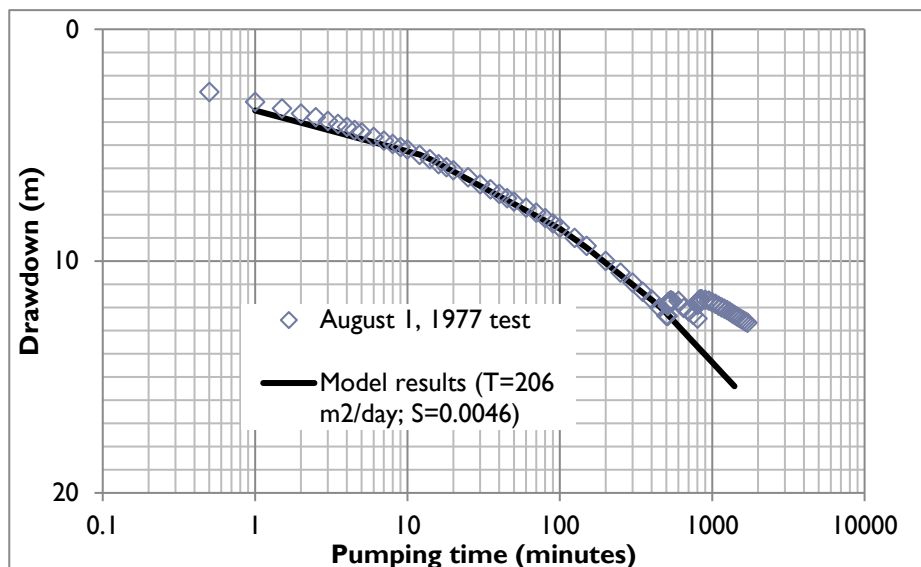


**Figure 3.1.** Plot of drawdown in well 786 from the 1977 test (open diamonds), and modelled drawdown of in the same well showing the effect of the buried channel (black line). The pumping rate was constant ( $1985 \text{ m}^3/\text{day}$ ).

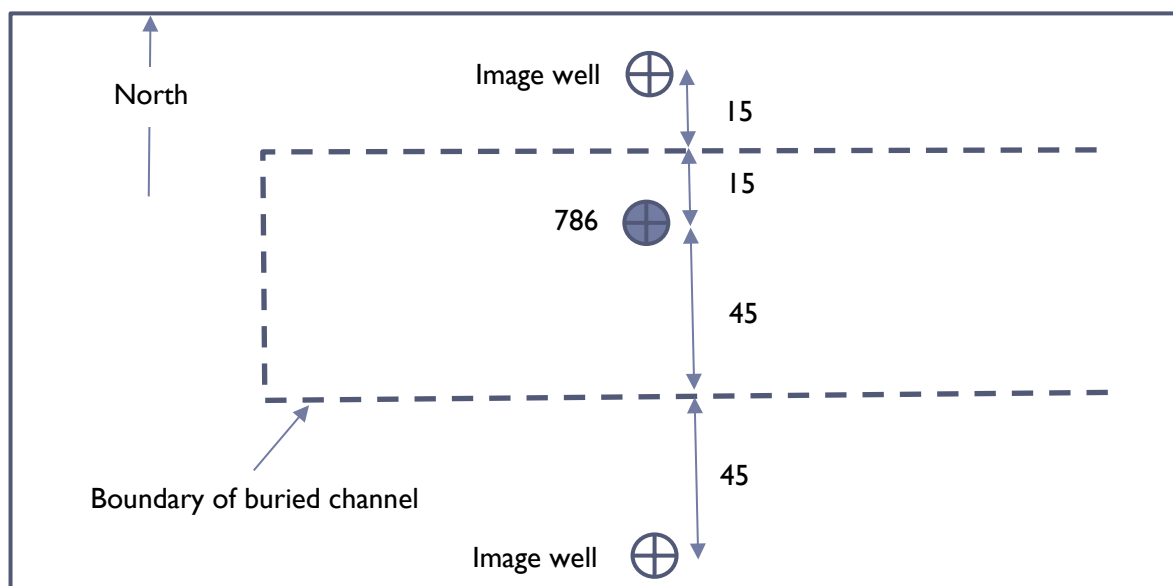


**Figure 3.2.** Schematic diagram showing location of well 786 in relation to inferred buried channel and imaginary pumping wells used to model the channel boundaries to the north and south.

A useful outcome of test drilling for new water supplies in Aquifer 206 is identifying areas where there are thicker units of sand and gravel. However, the variability in materials and thickness of Aquifer 206 means that even if a thicker sand and gravel sequence is encountered (as in well 786), the areal extent of

the unit needs to be considered in designing the pumping test and ultimately determining the well's long-term capacity.

### **3.1.2 Well 778 (WTN 84818)**

The only pumping test done on this well in 1992 (LHC, 1994) did not show evidence of bedrock boundaries.

### **3.1.3 Well 783 (WTN 85108)**

The only pumping test done on this well in 2006 (LHC, 2006) did not show evidence of bedrock boundaries.

### **3.1.4 Well 1452 (WTN 56015) and Well 1453 (WTN 56016)**

No pumping test data are available for these MBWD production wells.

## **3.2 Aquifer 207**

Eleven pumping tests were compiled for 6 bedrock wells, including MBWD production wells 1386, 1387, 21614, and 15603 (refer to Table 1.1). Pumping tests for three bedrock wells (1387, 21614, and 15603) were analyzed in detail to understand how the bedrock aquifer responds to pumping. In general, the following observations can be made:

- The nature of local bedrock fracturing (e.g., depth of fracture, fracture permeability and inter-connectedness) influences pumping behaviour and well capacity.
- Pumping tests for wells 1387, 21614 and 15603 all showed evidence of linear flow through bedrock fractures when the wells were initially pumped. As pumping continued, flow to the well eventually transitioned to radial flow. The initial period of linear flow when the rate of drawdown is gradually increasing with time can last a few hours to over a day.
- Radial flow models should not be applied in analyzing pumping behaviour dominated by this initial linear flow period because the rate of drawdown is still not constant; doing so may lead to errors in over-estimating well capacity and aquifer properties, like transmissivity, and under-estimating well interference.
- Use of diagnostic plots, including plotting the derivative of drawdown, proved useful in analyzing pumping behaviour in the bedrock wells.
- The pumping tests done a decade or more ago did not have the benefit of seasonal water level information provided by bedrock Observation Well 380. Some of those early tests were conducted during periods of seasonally higher water levels and that may, in part, explain the more favourable initial well capacity estimates for these wells.

### 3.2.1 Well 1387 (WTN 85151)

Pumping tests of well 1387 show drawdown behaves like an “ideal” aquifer after about a couple of hours of pumping. The lower static water level in the 2016 test compared to the 2009 test did not seem to affect the well’s specific capacity and calculated transmissivity.

### 3.2.2 Well 21614 (WTN 88224)

When well 21614 was test pumped in 2016 and 2017, it was noted that the pumping water level did not draw down with time like an “ideal” aquifer. Figure 3.3 is a diagnostic plot of both drawdown and the rate of drawdown (i.e., the derivative of the drawdown) with pumping time on a log-log graph for the 2017 test. This type of graph allows aquifer behaviour to be interpreted by comparing the drawdown and derivative of drawdown against a variety of analytical models representing different, “non-ideal” conditions (see Renard et al, 2009). Non-ideal conditions are those that violate the simple assumptions of horizontal radial flow to the pumping well. Figure 3.3 shows the rate of drawdown increasing steadily with time nearly to the end of the test, when the derivative curve starts to flatten out, indicating the onset of quasi-radial flow conditions.

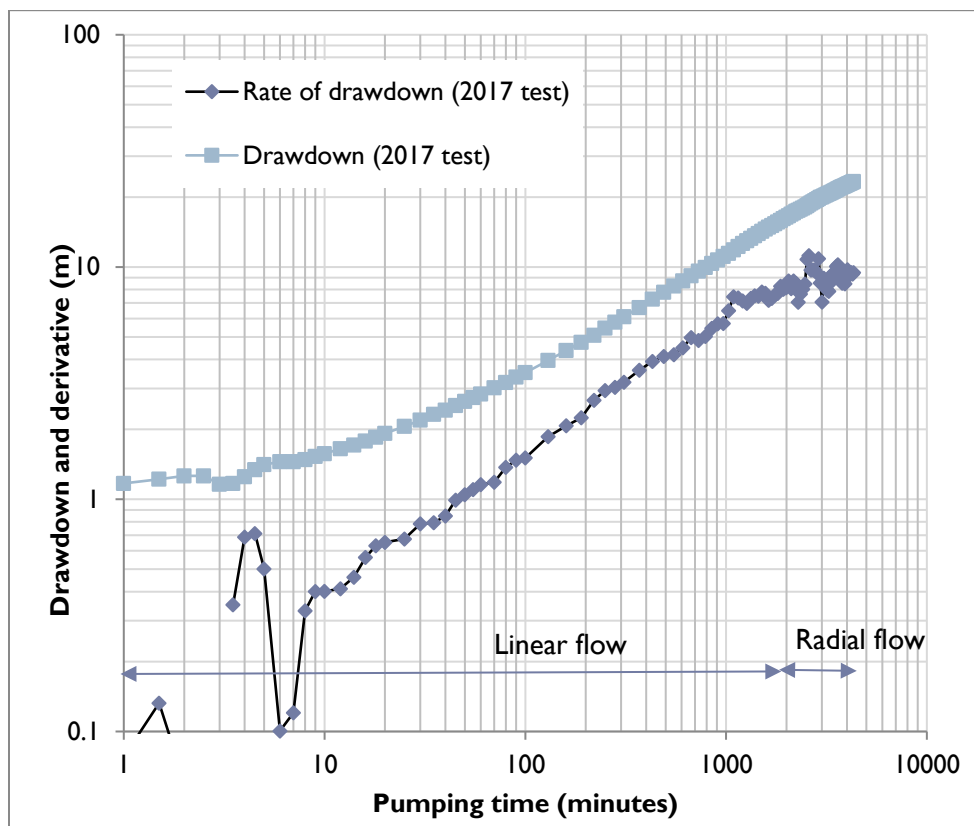


**Figure 3.3. Log-log plot of drawdown (blue squares) and rate of drawdown (dark blue diamonds) versus pumping time for well 21614 (2017 pumping test). Plot shows flow to pumping well is linear up to ~2000 minutes and transitions to radial flow thereafter (rate of drawdown becomes constant [flattens out]).**

The diagnostic plot for the 2017 test (Figure 3.3) shows that the drawdown and rate of drawdown fit the model of a pumping well drilled into a major, vertical water-bearing fracture (the drawdown plot lies above the derivative, by a factor of  $\sim 2$  times and the slope of the drawdown graph with log time is approximately 0.5, indicative of linear flow conditions (Renard et al, 2009 and Allen, 1999, respectively)). A schematic of groundwater flow to a pumping well intersecting a vertical fracture is shown in Figure 3.4, below. Conceptually, when a well intersecting a vertical fracture (Figure 3.4a) is pumped, at early pumping times, groundwater flows along the fracture to the pumping well, and flow is not radial but linear in 2 dimensions (hence the term “linear flow”; Figure 3.4b). As pumping continues into later times and the area of drawdown increases, flow to the fracture becomes more radial (Figure 3.4c). In the 2017 pumping test of well 21614, the linear flow period is evident until about 2000 minutes into the test (Figure 3.3). As pumping continues beyond about 2000 minutes to the end of the test, the flow regime begins to transition to radial flow, more typical of an “ideal” aquifer (where drawdown becomes constant with log time as evidenced from the derivative converging on a single value). It is not clear from the test whether radial flow conditions are fully reached (the rate of drawdown should plot as a flat line on the log-log graph).

Behaviour from the 2007 and 2009 tests for well 21614, and for the 2016 test of well 1387 also showed linear flow at early pumping times, transitioning to radial flow at later pumping times. The difference between the behaviour observed for these tests is the duration of the linear flow period differs, with linear flow lasting less than 1000 minutes for all except the 2017 test for well 21614.

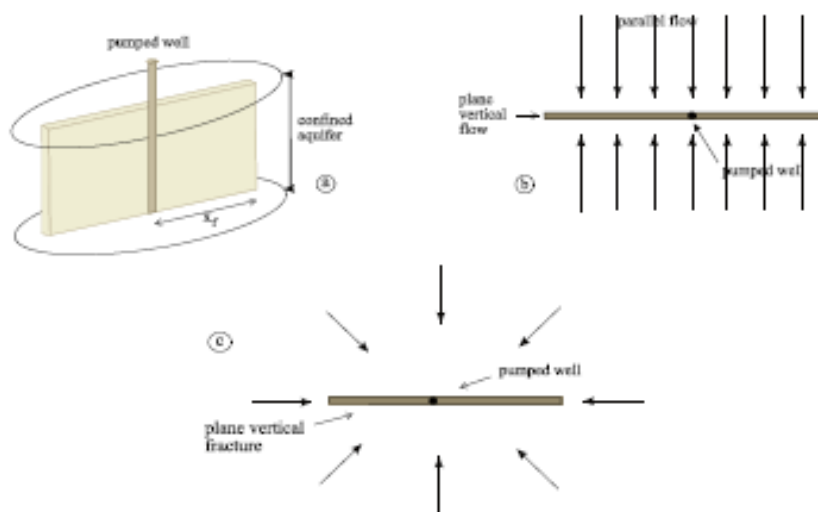


**Figure 3.4. Schematic of a pumping well drilled into a vertical bedrock fracture (a). At early pumping times, groundwater flows parallel within the bedrock to the fracture (linear flow) (b). At later times, as the area of drawdown grows, groundwater flow to the well becomes more radial (c) (from Allen, 1999).**

The practical implication is if radial flow has not been fully reached, application of the Province’s 100-day method for estimating well yields by extrapolating drawdown using the straight line method could result in over-estimation of the well’s capacity (see ENV, 1999). Application of models for an ideal aquifer could also result in an over-estimation of the aquifer’s transmissivity and under-estimate well

interference drawdown in neighbouring wells. Since it can take 1 day or more for wells completed in Aquifer 207 to transition to radial flow, it is important to use an appropriate model to interpret the early time pumping test data when behaviour is non-ideal. Use of an appropriate aquifer model, in this case for a pumping well drilled into a vertical bedrock fracture (Gringarten et al, 1975) yields an aquifer transmissivity of 4.64 m<sup>2</sup>/day. A similar transmissivity value (3.16 m<sup>2</sup>/day) was calculated from the 2016 test using the same model (see Table 3.1).

Review of the 2007, 2009, 2016 and 2017 tests of well 21614 showed that test conditions a decade ago were much different:

- The static water level in 2016 and 2017 was 35 to 40 m lower than in the 2007 and 2009 tests. This may in part be due to the fact that the 2016 and 2017 tests were done during a time of low seasonal water levels. It may also be that for the 2016 and 2017 tests, the water level in well 21614 was still in recovery from operational pumping.
- The lower static water level in the 2016 and 2017 tests likely also meant a lower aquifer thickness, which explains the lower calculated aquifer transmissivity (e.g., 3.7 m<sup>2</sup>/day from the 2016 and 2017 test compared to 6.7 m<sup>2</sup>/day from the 2007 and 2009 tests).

Storativity of the aquifer was estimated to be  $\sim 1.44 \times 10^{-4}$  from the 2009 pumping test of well 21614 (based on data from a nearby observation well (MBWD well 1387)).

### **3.2.3 Well 15603 (WTN 89731)**

In both the 2016 and 2006 pumping tests for well 15603, it appeared that as the pumping water level reached a depth of ~74 m or deeper, the rate of drawdown increased significantly (see Figure 3.5). This depth corresponds to a water-bearing fracture reported by the driller (at 74.7m depth). This suggests that if the pumping water level is drawn down below 74 m depth, the productivity of the well can be affected.

Similar to well 21614, the 2016 test for well 15603 was also carried out during the seasonally low water level period and test conditions were different than those for the 2006 test. The available drawdown, specific capacity and transmissivity were lower for the 2016 test, but the main limitation to this well's capacity appears to be the drawdown limit of 74 m in the well.

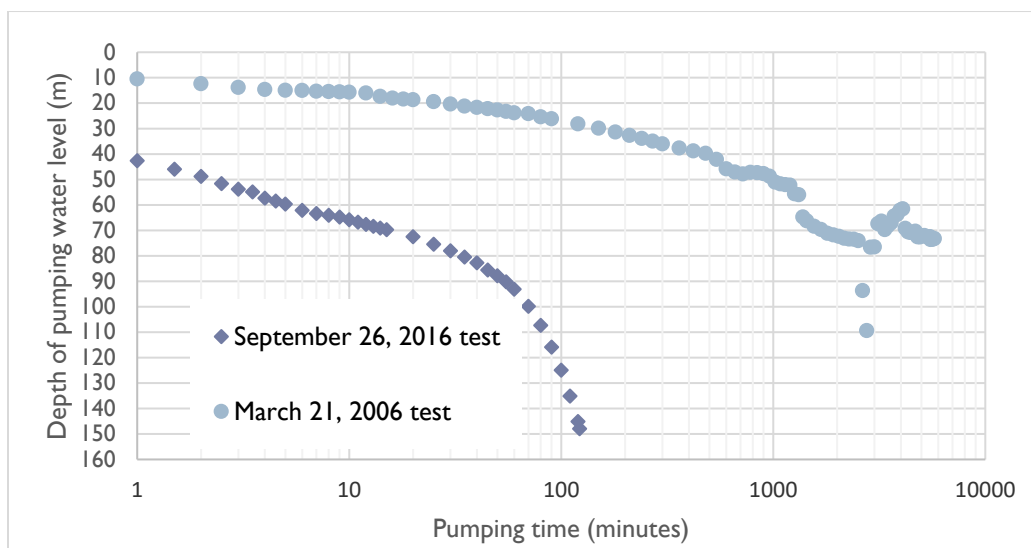


**Figure 3.5. Depth of pumping water level in well 15603 from the 2006 and 2016. Note rate of water level decline appears to increase significantly below ~74 m depth, corresponding to one of the reported water-bearing fractures.**

| Well ID or name | WTN   | Start date of test | SWL (m) | Transmissivity, T (m <sup>2</sup> /day) |                      |                       |                                   | S (-)                         | Transition to radial flow |
|-----------------|-------|--------------------|---------|-----------------------------------------|----------------------|-----------------------|-----------------------------------|-------------------------------|---------------------------|
|                 |       |                    |         | Gringarten et al, (1975)                | Cooper-Jacob, (1946) | Theis recovery (1935) | Gringarten and Witherspoon (1972) |                               |                           |
| 80-2            | 46804 | Jul, 1992          | 7.62    | N/C                                     | 0.28                 | N/C                   | N/C                               | N/C                           |                           |
| OW 380          | 46810 | Jul, 1992          | 5.32    | N/C                                     | 2.8                  | N/C                   | N/C                               | N/C                           |                           |
| 15603           | 89731 | Mar 20, 2006       | 3.34    | <b>3.04</b>                             | N/C                  | <b>2.95</b>           | N/C                               | N/C                           | ~0.1 day                  |
| 15603           | 89731 | Sept 26, 2016      | 29.28   | <b>1.56</b>                             | N/C                  | <b>1.2</b>            | N/C                               | N/C                           | <0.1 day                  |
| 1387            | 85151 | Dec 16, 2004       | 11.43   | <b>14.58</b>                            | N/C                  | <b>8.8</b>            | N/C                               | N/C                           |                           |
| 1387            | 85151 | Oct 6, 2016        | 58.80   | <b>19.33</b>                            | N/C                  | <b>19.3</b>           | N/C                               | N/C                           | ~1 day                    |
| 1386            | 85275 | Mar 7, 2007        | 18.75   | N/C                                     | 16.7                 | 11.7                  | N/C                               | N/C                           |                           |
| 21614           | 88224 | Jun 19, 2007       | 47.1    | N/C                                     | 7.7                  | 6.8                   | N/C                               | N/C                           |                           |
| 21614           | 88224 | Jun 20, 2009       | 38.88   | <b>6.54</b>                             | <b>6.97</b>          | <b>6.01</b>           | <b>6.27</b>                       | <b>1.44 × 10<sup>-4</sup></b> | ~2-3 days                 |
| 21614           | 88224 | Sept 19, 2016      | 84.3    | <b>3.16</b>                             | <b>3.46</b>          | <b>4.20</b>           | N/C                               | N/C                           | ~2 days                   |
| 21614           | 88224 | Oct 4, 2017        | 80.88   | <b>4.64</b>                             | <b>4.34</b>          | <b>2.56</b>           | N/C                               | N/C                           | ~2-3 days                 |

**Table 3.1. Comparison of aquifer hydraulic properties calculated from pumping tests of bedrock wells in the MBWD area. N/C = not calculated; SWL = Static water level; S = Storativity.**

#### 4. AREAS OF PUMPING STRESS

One of the objectives of this study was to identify areas within Aquifers 206 and 207 that are under stress from pumping. Knowing where areas are stressed from pumping helps inform development of additional groundwater supply away from these stressed areas. Pumping stress is associated with drawdown in the groundwater level from well pumping. The Cooper-Jacob equation (Equation 1 below) was used to model drawdown in the groundwater level in Aquifers 206 and 207, based on the expected pumping rates of the MBWD wells. The Cooper-Jacob equation models drawdown over time around a pumping well completed into a simplified, ideal aquifer. A simplified, ideal aquifer is one that is spatially extensive and has uniform thickness and uniform permeability (or hydraulic conductivity). While Aquifers 206 and 207 are not simple, ideal aquifers, the Cooper-Jacob model (Cooper-Jacob, 1946) was used to represent drawdown in both aquifers for illustrative purposes. The equation below depicts the change in head (water level) due to pumping:

$$h - h_0 = \frac{2.3Q}{4\pi T} \log \left( \frac{2.25Tt}{r^2S} \right) \quad \text{[Equation 1]}$$

where:

$h-h_0$  is the drawdown (change in head) at a given location and a given time;

$Q$  is the pumping rate (must be constant for the equation);

$T$  is the aquifer's transmissivity (one value because the aquifer is uniform);

$t$  is the pumping time;

$r$  is the distance between the pumping well and a given location;

$S$  is the aquifer's storativity (one value because the aquifer is uniform).

To calculate and map drawdown in each aquifer in the study area using the Cooper-Jacob equation, the following information was required:

- The spatial location of the pumping wells;
- The long-term operational pumping rate for the wells;
- The specified period of pumping; and
- The transmissivity and storativity of the aquifer.

Each of these input parameters are briefly discussed below.

Location of the pumping wells. The known main pumping wells in Aquifers 206 and 207 within the study area are the MBWD wells. Other wells exist within the study area but most are assumed to be diverting water for domestic purposes only (a small quantity which is likely <2 m<sup>3</sup>/day in most cases). As existing groundwater users become licensed over time, a more complete understanding of the authorized water uses in the study area may be obtainable.

Pumping rate for the wells. The individual long-term pumping rates for the MBWD wells 786, 783, 1452, 1453, and 1387 were taken from the well capacity rating in the Associated Engineering (AE) (2017) report. The long-term pumping rates used for wells 778, 1386, 21614, and 15603 were more conservative than the rated capacities reported in AE (2017) and are based on review of the pumping test results in this study. Pumping rates used for the drawdown calculation are shown in Table 4.1 and are assumed to be constant. Using the individual well capacity (instead of what was actually diverted historically (i.e., AE (2017) and Thurber (2016a)) provides a picture of what drawdowns may look like when the current MBWD wells are pumping at their intended capacity in the future.

| MBWD production well | Well capacity used in drawdown calculation (m <sup>3</sup> /day) | (L/s) | Comment                                                                                                                                                                                              |
|----------------------|------------------------------------------------------------------|-------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 786                  | 907                                                              | 10.50 | Value as reported in AE (2017).                                                                                                                                                                      |
| 778                  | 326                                                              | 3.77  | Value as reported in AE (2017).                                                                                                                                                                      |
| 1452                 | 164                                                              | 1.90  | Value as reported in AE (2017).                                                                                                                                                                      |
| 1453                 | 216                                                              | 2.50  | Value as reported in AE (2017).                                                                                                                                                                      |
| 783                  | 130                                                              | 1.50  | Value as reported in AE (2017).                                                                                                                                                                      |
| 15603                | 15                                                               | 0.17  | Value used for calculation is much lower than the reported value in AE (2017) of 261 m <sup>3</sup> /day because rate of drawdown became significant below a depth of ~74 m in the well (see 3.2.3). |
| 1387                 | 900                                                              | 10.42 | Value as reported in AE (2017).                                                                                                                                                                      |
| 1386                 | 318                                                              | 3.68  | Value used for calculation is lower than the reported value in AE (2017) of 370 m <sup>3</sup> /day based on review of test results in this study.                                                   |
| 21614                | 260                                                              | 3.01  | Value used for calculation is slightly lower than the reported value in AE (2017) of 590 m <sup>3</sup> /day based on review of test results in this study (see 3.2.2).                              |

**Table 4.1. Pumping rates used to calculate drawdown in Aquifers 206 and 207 caused by pumping of the MBWD production wells.**

The specified period of pumping. The pumping time was assumed to be 100 continuous days. This 100-day period was chosen because it represents the driest 3 months of the year (August-October) when water demand is also relatively high. It is the same period that the Province of BC typically uses to calculate long-term well capacity.

Aquifer transmissivity and storativity. The transmissivity (T) values used for Aquifers 206 and 207 were obtained from individual pumping tests compiled in this study. A single T value is required for the Cooper-Jacob equation (recall the aquifer being modelled has to be a simplified, ideal aquifer). The overall T value used for each aquifer was based on the geometric mean of available values, as shown in Table 4.2. Geometric mean is a more meaningful representation of “average” than the arithmetic average.

Storativity is an aquifer parameter that can only be calculated if drawdown in an observation well was monitored during a pumping test. Data for drawdown in observation wells were sparse but storativity is not considered a sensitive parameter in the Cooper-Jacob equation (i.e., does not greatly affect the

answer). Storativity values used for calculating drawdowns were taken from values compiled by Carmichael (2014) (see Table 4.2).

| Parameter                            | Maximum calculated | Average | Geometric mean | Minimum calculated | Value used in calculating drawdown |
|--------------------------------------|--------------------|---------|----------------|--------------------|------------------------------------|
| <b>Aquifer 206</b>                   |                    |         |                |                    |                                    |
| Transmissivity (m <sup>2</sup> /day) | 1620               | 198     | 54             | 0.1                | 54                                 |
| Storativity (-)                      | -                  | -       | -              | -                  | 0.02 (from Carmichael, 2014)       |
| <b>Aquifer 207</b>                   |                    |         |                |                    |                                    |
| Transmissivity (m <sup>2</sup> /day) | 19                 | 6.1     | 3.2            | 0.3                | 3.2                                |
| Storativity (-)                      | -                  | -       | -              | -                  | 0.00064 (from Carmichael, 2014)    |

**Table 4.2. Summary of aquifer hydraulic parameters (transmissivity and storativity) for Aquifers 206 and 207 (note storativity values are lacking for both aquifers).**

To be able to plot contours of specific values of drawdown on a map, Equation 1 was re-arranged to allow the radial distance (r) for specific values of drawdown to be calculated for each MBWD pumping well (see Equation 2). By doing this, we were able to plot circular areas (radii of influence, or ROI) for various ranges of drawdown for each aquifer (e.g., ≥1 m drawdown; ≥3 m drawdown; ≥5 m drawdown, etc. The resulting drawdown estimated for MBWD wells in Aquifer 206 is shown in Map 4a and the drawdown for MBWD wells in Aquifer 207 is provided in Map 4b, following the text of the report.

$$r = \sqrt{\left( \frac{2.25Tt}{S \cdot 10^{\left( \frac{4\pi T(h-h_0)}{2.3Q} \right)}} \right)} \quad [\text{Equation 2}]$$

Map 4a shows that pumping of MBWD wells 783, 786, 1452 and 1453 induces drawdown in the northern portion of Aquifer 206. Drawdown less than 1 m was not mapped because it was considered within the range of seasonal water level fluctuation for the aquifer and therefore deemed not significant with respect to interference impact. Drawdown in Aquifer 206 was generally estimated to be on the order of between 1 m and 3 m but approaches 5 m near well 786.

In reality, actual drawdown near any given well may be different than modelled here, greater if the aquifer is not as thick or transmissive, or less if the aquifer is locally thicker, more transmissive, or if the aquifer intercepts a source of recharge (like a stream). In the specific case with well 786 completed into sediment-filled channels incised in bedrock, the drawdown there may be greater than predicted by the Cooper-Jacob equation because aquifer thickness is locally bounded to the north and south (not areally extensive). The drawdown area may also be locally more cigar-shaped oriented to the west and east, as opposed to perfectly circular.

Map 4b shows that pumping of MBWD wells 1386, 1387, 21614, and 15603 results in an estimated drawdown surface that is also situated in the northern part of the MBWD service area. Similar to the rational for Map 4a, drawdown of less than 5 m was not mapped in Map 4b. Drawdown in bedrock is

determined to be greater than that in the overlying sand and gravel because the transmissivity of Aquifer 207 is more than one order of magnitude less than that of Aquifer 206, however available drawdown is significantly more.

In reality, the drawdown area in the bedrock will not likely be perfectly circular because fractures from which water is diverted have specific orientations; the drawdown areas may be more irregular-shaped, depending on the orientation of the fractures. Drawdown areas in fractured bedrock is hard to predict and can practically only be observed in observation wells under controlled pumping conditions (like in a pumping test). Also, drawdown is expected to be greater than modelled if bedrock wells are over pumped, resulting in dewatering of fractures.

Despite some conceptual limitations, Maps 4a and 4b are useful in showing where pumping stress in both aquifers generally occur. Pumping stress in both aquifers is inferred to be highest in the northern part of the MBWD service area (where the majority of wells are located) and lowest in the southeast quarter of Aquifer 206 and in the southern half of the MBWD service area for Aquifer 207.

Pumping stress is discussed further in 5.4.1 (Annual Water Budgets for Aquifers 206 and 207).

## **5. CONCEPTUAL MODEL OF AQUIFERS 206 AND 207**

The conceptual model of an aquifer represents the understanding of the processes that convey water into and out of an aquifer, plus the resulting changes in volume of water (surplus/deficit) within the aquifer with time (inflows and outflows do not always zero out at any given time). Since Aquifer 206 directly overlies Aquifer 207, our conceptual understanding of both aquifers will be presented and discussed together. This is depicted schematically in Figure 5.1 below. The components of Figure 5.1 are discussed in more detail in the following section.

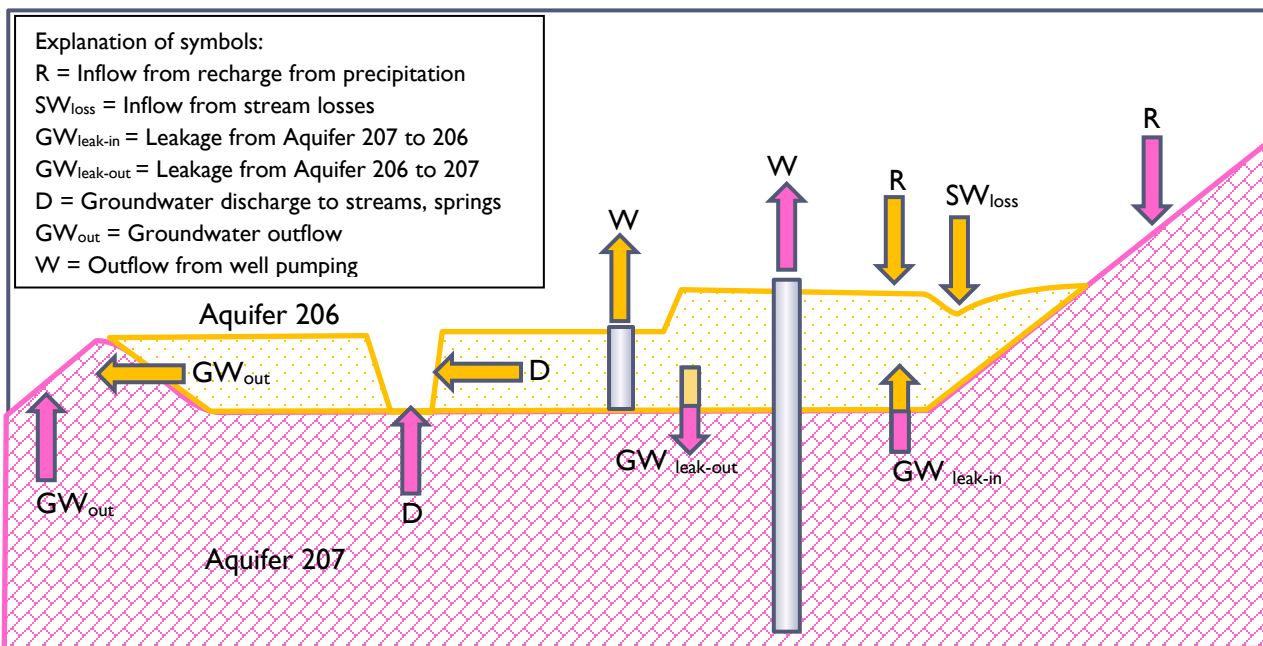


**Figure 5.1. Schematic diagram of Aquifers 206 and 207 and the major water inflow and outflow processes.**

## 5.1 Inflow of Water to the Aquifers

### 5.1.1 Precipitation Recharge

The main source of water inflow into both aquifers is from infiltration of precipitation. The portion of precipitation that falls directly on the aquifers and infiltrates into the ground to replenish the underlying groundwater is termed “precipitation recharge” (R in Figure 5.1). Historical data from former monitoring of Provincial Observation Well 350, which is completed in Aquifer 206 and located south and uphill of Wheelbarrow Springs, show that the main recharge period for Aquifer 206 occurs in the spring (March to May) and typically lags 2 to 4 months following the peak rainy season (see Figure 2.1 in Section 2.3.2 (Recharge)).

SLR (2017) estimated that, in an average climate year, Aquifer 206 receives about 0.36 m/yr of recharge from precipitation. For a dry climate year and wet climate year, SLR (2017) estimated recharge values of 0.24 m/yr and 0.60 m/yr, respectively. Recent unpublished work by ENV, which calculated recharge from water level fluctuations recorded in historical monitoring wells (including Provincial Observation Well 350) suggested SLR (2017)’s estimates of recharge for Aquifer 206 are reasonable.

SLR (2017) estimated R for Aquifer 207 to be 0.43 m/yr in an average climate year, a slightly higher value than that for Aquifer 206. For a dry climate year and wet climate year, SLR (2017) estimated recharge values for Aquifer 207 of 0.29 m/yr and 0.71 m/yr, respectively. Recharge to Aquifer 207 from precipitation likely occurs in areas where bedrock outcrops are exposed at surface, or where there is marginal overburden thickness. Provincial Observation Well 380, which is completed in bedrock and

located in Mill Springs off of Kinnoull Crescent, shows that the period of recharge for Aquifer 207 slowly builds from October through the winter months and peaks at about the same time (April to May) as Aquifer 206 (see Figure 2.2 in Section 2.3.2 (Recharge)). Assuming that water level trends at Well 380 are representative of the conditions in Aquifer 207, this slow build-up is unexpected. The groundwater levels in Observation Wells 65, 240, and 343 drilled into the same type of bedrock in the Saanich Peninsula respond much more quickly with the on-set of late Fall rains in November, which is expected of a fractured bedrock aquifer with little ability to store significant quantities of water. The slow rise in groundwater level with the onset of Fall rains suggests it takes Aquifer 207 6 to 7 months to recover fully (unlike other typical bedrock aquifers in the region). Long-term pumping could also further delay complete recovery. The reason for the long recovery is currently unknown, but suggests there may be significant void spaces in the bedrock that are drained seasonally and requires time to re-fill. While Observation Well 380 is drilled into granitic rock with likely very low porosity, the bedrock to the south (Bonanza Group and Quatsino Formation) is known to have limestone, which may contain karstic features having higher porosity. These voids, if present, could help explain the seasonal groundwater level response for Aquifer 207.

### 5.1.2 Inflow from Stream Losses

SLR (2017) hypothesizes that Aquifer 206 receives some water from seepage losses from Handysen Creek ( $SW_{loss}$  in Figure 5.1), based on the difference between the stream and deeper groundwater levels and an assumed seepage rate.

### 5.1.3 Leakage Between Aquifers 206 and 207

The areas of inferred upward gradient in Map 3 show that in the southern, higher elevation portion of the study area, groundwater from the underlying Aquifer 207 may leak upward into overburden. While this leakage may result in a net inflow to Aquifer 206, it also results in an outflow from Aquifer 207. Similarly, as shown in Map 3, there is a downward flow gradient in the central portion of Aquifer 206. This may result in a net loss from Aquifer 206 and an inflow to Aquifer 207. Leakage into Aquifer 206 from Aquifer 207 and out of Aquifer 206 into Aquifer 207 are represented by the symbols  $GW_{leak-in}$  or  $GW_{leak-out}$ , respectively in Figure 5.1. Relative to infiltration of precipitation, inter-aquifer flow is expected to be a relatively minor component of recharge and occurs on a local as opposed to aquifer-wide scale.

## 5.2 Outflow of Water from the Aquifers

Groundwater leaves the aquifers in various ways: 1) withdrawal via pumping wells, 2) lateral flow beyond the aquifer's boundary, 3) leakage into the adjoining aquifer, and 4) discharge to surface streams.

SLR (2017) calculated the quantity of water leaking downward from Aquifer 206 to Aquifer 207 ( $GW_{leak-out}$  in Figure 5.1), based on the entire Aquifer 206 area and assuming a specific hydraulic gradient and bedrock permeability. Map 3 indicates that the southern end of Aquifer 206 likely receives upward leakage from Aquifer 207, however. Therefore, the area and corresponding amount of downward

leakage may not be as high as SLR (2017) initially assumed. The water budget for Aquifer 206 has been updated by ENV to reflect this.

### 5.2.1 Outflow of Groundwater Discharge to Streams, Springs

Groundwater in both aquifers likely discharges to local creeks, such as to Hollings Creek and the unnamed creeks flowing east and northeast to the ocean east of Highway 1, as well as local springs like Wheelbarrow Springs. This process is represented by the symbol D in Figure 5.1. Flow in streams and springs during the late spring and summer months is evidence that streamflow is derived from groundwater.

### 5.2.2 Groundwater Outflow

Groundwater flows beyond the aquifer boundaries, for example groundwater in Aquifer 207 flows to the ocean ( $GW_{out}$  in Figure 5.1). This quantity is calculated based on assumed values of gradient and hydraulic conductivity.

### 5.2.3 Well Pumping

Another process of groundwater outflow from the aquifers is diversion of water from well pumping (W in Figure 5.1). Unlike the other outflow processes, well pumping is an active process that occurs as a result of human demand on water. Pumping can change the various outflows from the aquifers from their natural states. For example, excessive pumping of groundwater from Aquifer 206 will lower the aquifer's water level around the pumping wells, resulting in a decrease in downward leakage to Aquifer 207. Excessive pumping from Aquifer 206 will cause discharge to local streams to decrease also. In their water budget calculation, SLR (2017) conservatively assumed the water pumped from wells is 100% consumed with none returning back to the aquifers, whereas in reality, some of the pumped water returns to the subsurface via septic fields and irrigation return flows. This inter-dependence of pumping effects on other inflow or outflow processes is currently not incorporated in the SLR (2017) water budget model.

## 5.3 Change in Water Storage

Change in the volume of water stored in an aquifer (represented by  $\Delta S$  in Equation 3 below) reflects the imbalance that typically exists between inflow and outflow at any given time. This ever-changing storage is reflected in the groundwater level rising and falling over the seasons or over the years. Groundwater levels typically rise in the spring because there is more inflow than outflow; groundwater level falls over the summer to fall because there is a lack of inflow to balance outflow.

This change in storage over time (water level over time) is what water system operators and government water managers measure in observation wells to assess if well pumping is sustainable or not. If groundwater levels continually decline over time, it may be a sign that well pumping is not sustainable.

## 5.4 Water Budgets for Aquifers 206 and 207

The inflow and outflow processes can be expressed as a water budget equation. Equation 3 below represents the various inflow and outflow processes discussed for Aquifers 206 and 207:

$$R + GW_{leak-in} + SW_{loss} = W + GW_{leak-out} + GW_{outflow} + D + \Delta S \quad \text{[Equation 3]}$$

where:

R is the annual recharge;

$GW_{leak-in}$  is the leakage of groundwater into one aquifer from another;

$SW_{loss}$  is the inflow of water from overlying streams;

W is pumping from wells;

$GW_{leak-out}$  is the leakage of groundwater out from one aquifer into another;

$GW_{outflow}$  is groundwater that laterally flows out of the aquifer (beyond its boundaries);

D is the discharge of groundwater to streams, springs and wetlands; and

$\Delta S$  is the change in storage or surplus/deficit in the aquifer.

The desktop study completed by SLR (2017) to quantify the water budgets for aquifers in the Cobble Hill-Mill Bay area, including Aquifers 206 and 207, revealed several key findings. A summary of these key findings and recent work by ENV to refine the water budget for Aquifer 206, is provided in the sections below.

### 5.4.1 Annual Water Budget for Aquifers 206 and 207

As a result of their water budgets, SLR (2017) estimated that there is an annual water deficit for all three climate scenarios (average, dry and wet years) for Aquifer 206. Aquifer 206 was identified as having the highest pumping stress of all the aquifers in the region. Their finding for Aquifer 207 is that the aquifer has a slight annual deficit only in the dry year scenario; generally, the aquifer has a surplus of water in most years.

If we look at the ratio of pumping withdrawal to precipitation recharge (W/R), they tell a similar story regarding overall stress of the aquifers (see Table 5.1). W/R is proposed by Vrba and Lipponen (2007) as one of the indicators of groundwater sustainability, and we find it useful though caution that it is a very simple ratio and is only one indicator of relative stress. The ratio of W/R is relatively high for Aquifer 206 (~70% for an average climate year and just over 100% for a dry climate year) and relatively light for Aquifer 207 (7% for an average climate year and just over 10% for a dry climate year). These percentages are based on the intended capacity of the MBWD production wells as reported by Associated Engineering Ltd. (2017) to reflect aquifer conditions in the future when MBWD is exercising its full water rights. The low W/R ratio for Aquifer 207 is, in part, due to the relatively high amount of

recharge estimated for Aquifer 207, which assumes that water infiltrating into the soil will eventually reach the underlying bedrock. It is important to understand that accessing this apparent abundance of water in 207 is not straightforward because it depends on encountering discrete water-bearing fractures and their locations at depth are hard to predict.

| Aquifer | R (m/yr)       | W (m/yr) | W/R (%)      | Notes                                                                                                                                                                                                                           |
|---------|----------------|----------|--------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 206     | 0.24-0.36-0.59 | 0.245    | 42%-69%-103% | W/R is calculated based on: <ul style="list-style-type: none"> <li>a dry, average and wet climate year</li> <li>the pumping rates for MBWD production wells are from Table 3 (excludes other private domestic wells)</li> </ul> |
| 207     | 0.29-0.43-0.71 | 0.03     | 4%-7%-11%    |                                                                                                                                                                                                                                 |

**Table 5.1. Indicator of annual well pumping to precipitation recharge for Aquifers 206 and 207.**

Deficit conditions in all three climate scenarios for Aquifer 206 by SLR's estimates imply that the yield limit of the aquifer has been reached. We note, however, that this finding is based on two conservative assumptions:

- 1) All water diverted is 100% consumed, and
- 2) Aquifer 206 does not receive any leakage from Aquifer 207.

In our opinion, these assumptions will tend to over-estimate the deficit condition. In most areas, unless it is conveyed away (e.g., through a municipal sewage system with ocean discharge), a portion of diverted water returns back to the aquifer and is not 100% consumed. In addition, mapping of groundwater levels shows that an upward gradient exists in the southern-most portion of Aquifer 206 (see Map 3), suggesting Aquifer 206 receives leakage upward from underlying Aquifer 207.

The water budget presented by SLR (2017) also does not, at present, reflect responses of inflow and outflow processes (e.g., leakage between Aquifers 206 and 207) due to increased pumping. Rather, increased pumping results in a decreasing surplus or growing deficit ( $\Delta S$ ) of the water budget.

#### 5.4.2 Uncertainties with Water Budgets

The water budget completed by SLR (2017) for both aquifers is essentially based on Equation 3. Equation 3 contains seven processes that need to be quantified to calculate the surplus/deficit ( $\Delta S$ ) for each aquifer. Calculations based on desk-top reviews of available information typically contain a significant degree of uncertainty because many of these processes are quantified based on assumed textbook values of aquifer properties.

A water budget can be strengthened over time as new data and information become available. Another way to make the water budget more robust is to calibrate the monthly surpluses and deficits with groundwater levels from observation wells. In the past year, ENV has started using historical groundwater level data from Observation Well 350 to help calibrate the water budget for Aquifer 206.

The recharge to bedrock calculated by SLR (2017) assumes that all the water that has infiltrated into the soil will reach the underlying bedrock. As recharge is a main input process to Aquifer 207, it is important to increase the confidence of this initial estimate. This may be done using other methods of estimation and measurement (e.g., numerical modelling, determining outflows from the bedrock).

As the major water user in the area, accurate historical and on-going data on monthly and annual pumping withdraws of MBWD production wells would eliminate uncertainty for that parameter (W) in equation (3) and aid in calibration of the ENV water budget estimates. Measurement of stream flows during the dry season would also be helpful in providing data to verify assumed stream seepage rates from Aquifer 206. Rathfelder (2018; Pers. Comm.) indicated that ENV has approval to measure streamflow in the study area in 2018/19. Finally, hydraulic conductivities from the pumping tests compiled from this study can also be used in the water budgets to help estimate leakage rates and reduce the uncertainty in the water budgets.

## **6. IMPLICATIONS FOR FUTURE GROUNDWATER DEVELOPMENT**

This study has increased understanding of groundwater development in the area and its implications on managing current supplies. This information can also be used in exploring for additional future groundwater supplies. The main points for current and future groundwater development for MBWD are presented below:

- Long-term capacity of wells 786 (completed into Aquifer 206) and wells 15603 and 21614 may be less than originally predicted, which could impact the use of the wells for supply as originally intended.
- Local geology can impact long-term pumping behaviour, but relevant characteristics are hard to observe in a pumping test that lasts one to several days. Specifically, drawdown may be greater (and supply may be less) than predicted from a short-term pumping test in areas of Aquifer 206 that are bounded. Furthermore, possible higher porosity zones in the bedrock to the south in Aquifer 207 may be causing seasonal recovery in the bedrock to be slower than expected.
- Pumping stress appears to be high in the north half of the MBWD service area and light in the southern half. Based on this information, it may be worthwhile to focus future exploring efforts for additional groundwater supply on the southern portions of the service area.
- Aquifer 206 is more stressed than Aquifer 207, based on the W/R index.
- Exchange of groundwater between Aquifers 206 and 207, and both aquifers' connection to local streams, are uncertain at this time.

## **7. RECOMMENDATIONS**

### **7.1 Annual Testing to Monitor Well Performance**

The MBWD wells should be tested annually to monitor specific capacity and well performance with time. This is particularly important for those wells (1386, 1452, 1453) where initial pump testing data

and information are not available. WWAL provided a draft plan to MBWD for annual performance testing of production wells in August 2017.

## 7.2 Pumping Test Information for Wells I452 and I453

Pumping test data for MBWD production wells I452 and I453 (Aquifer 206) were not available to WWAL for this study. This creates a data gap with respect to our understanding of the hydrogeology of Aquifer 206 and baseline performance for these two wells. This should be addressed by searching for and acquiring these data and incorporating the results (if available) into the database developed in this study. If original data are unavailable, short-term baseline pumping tests (as per 7.1) on these wells should be conducted.

## 7.3 Measure and Record Quantities Diverted from Each Well

To assist with well performance, aquifer yield, and water budget assessments, and to verify beneficial use under the water licences, accurate measurement and recording of water use is important. To obtain this, it is recommended that MBWD measure and record the monthly and annual quantity of water diverted from every production well and from the springs separately (where it is not already being done). These data should be recorded in a digital database (e.g., Excel spreadsheets). Having data in a digital database makes data sharing easier and less costly. The database should include at least the following information in Table 7.1. Any historical pumping information for the MBWD production wells should also be entered.

Where it is not done so already, MBWD should also consider metering each well separately so diversion from each well does not have to be estimated.

| Well 786           |                           |                                 |                 |                                |
|--------------------|---------------------------|---------------------------------|-----------------|--------------------------------|
| Date (dd-mmm-yyyy) | Reading (m <sup>3</sup> ) | Monthly total (m <sup>3</sup> ) | Observer (name) | Annual total (m <sup>3</sup> ) |
| 01-02-2019         | 1663704                   | 13500                           | DM              | 13500                          |
| 01-03-2019         | 1675709                   | 12005                           | DM              | 25505                          |

**Table 7.1. Example of how quantity diverted can be recorded.**

## 7.4 Compile Water Quantity and Water Level Data for the MBWD Production Wells

Historic water quantity and water level data available for MBWD production wells should be compiled into a database. This data can be used to help calibrate water budgets and would strengthen our understanding of aquifer performance over time. This task would involve compiling the data for each available well and entering them into a spreadsheet format.

## 7.5 Diagnostic and Derivative Plots to help Interpret Pumping Tests

In assessing pumping test results, it should be standard practice to use diagnostic plots, including plotting the derivative of drawdown. This approach helps with interpretation of the pumping response and with

selection of the appropriate analytical model to use to calculate aquifer hydraulic properties (i.e., T, S) and to estimate long-term well capacity.

## 7.6 Review of LIDAR Data and Lineament Analysis

The long recharge period for Aquifer 207 recorded from Observation Well 380 should be further assessed as it may limit Aquifer 207's ability to recover fully. We understand the Cowichan Valley Regional District (CVRD) has given MBWD access to LIDAR data collected for the area. These data should be reviewed to see if there are features, such as sinkholes, that indicate higher than expected bedrock porosity in the nearby area.

Predicting where fractures will be encountered in drilling is highly uncertain, however an analysis of fracture location and density from aerial photographs can help identify areas of higher density fractures or faults to help target drilling locations. Use of geophysics (e.g., electro-magnetic (EM)) may also help identify areas where the bedrock has less resistance and greater water supply potential (see 7.7 below).

## 7.7 Remote Sensing to Inform Drilling

In the past year, a couple of suggestions have been made by the MBWD and CVRD regarding use of remote sensing techniques to help identify areas with greater groundwater potential for exploration and development. Two technologies mentioned are: InSAR and SKYTEM. Both these technologies are briefly discussed here.

**InSAR:** Interferometric synthetic aperture radar (InSAR) utilizes satellite images over time to detect millimeter-scale movements or deformation of the earth's surface, such as from landslides and subsidence. Measurement density can be as high as 100,000/km<sup>2</sup> (one measurement per every 10 m<sup>2</sup>). With respect to groundwater resource application, InSAR technology could potentially detect consolidation of sediments underlying the land surface as a result of groundwater level changes; InSAR does not appear, however, to be able to detect direction and rate of groundwater flow, nor thickness and permeability of the underlying sediments.

**SkyTEM:** SkyTEM is a helicopter-borne EM survey technique. This technology was successfully applied recently in the Peace River region of BC to help the oil and gas industry explore for groundwater (Morgan and Allen, 2018). EM measures the relative conductance of the ground. Table 7.2 shows the conductance of some common hydrogeologic conditions.

| Hydrogeologic conditions   | Lower conductance       | Higher conductance                       |
|----------------------------|-------------------------|------------------------------------------|
| Degree of water saturation | Dry                     | Wet                                      |
| Water quality              | Clean, less mineralized | Contaminated, saline, highly mineralized |
| Lithology                  | Sand, gravel            | Clay                                     |

**Table 7.2. Conductance of some common hydrogeological conditions.**

Remote Sensing technologies require specialized methods to process and interpret the data and they do not replace the need to verify geology via drilling. However, the feasibility of applying these technologies, especially ground EM should be explored further as they may help further target test drilling.

## **7.8 Additional Observation Wells**

Additional observation well(s) should be considered to begin to better understand groundwater conditions in the MBWD service area. FLNR has recently established a new observation well completed into Aquifer 206 (Observation Well 470 (WTN 114847)) in the Wheelbarrow Springs area near well 786 to replace Observation Well 350. Another area that would benefit by installation of monitoring well(s) is the southern part of the MBWD service area. Where undertaken, monitoring well drilling would also assist with groundwater exploration.

## **7.9 Groundwater Exploration**

Future groundwater exploration in Aquifer 206 should be considered in areas with thick overburden (for example, Area C on Map 1). Airborne or ground-based EM surveys could help to identify areas with high conductance (e.g., wetter areas in the subsurface) and are relatively low cost. However, information from EM data still need to be confirmed through test-drilling.

For Aquifer 207, both the Island Plutonic Suite and the Bonanza Group are low permeability bedrock types. Successful wells have been drilled in these units closer to regional faults (e.g., Shawnigan and San Juan faults), or large open fracture systems. Where geologic features occur, such as the Shawnigan fault, drilling in such targets may yield more successful wells. Sites with mapped carbonate deposits and/or karst features may also yield more successful wells. Air photos and LIDAR data could be used to identify geologic structures and potential karst features in future studies.

To minimize potential for well interference between wells, potential target sites for new wells should fall outside areas of significant ROI, as depicted on Maps 4a and 4b,

## **7.10 Water Allocation Planning and Water Allocation Restrictions**

Since the 1990's ENV has developed water allocation plans for all watersheds on Vancouver Island and the major Gulf Islands (<https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-planning-strategies/water-allocation-plans>). A water allocation plan reviews the water availability and water demand within a watershed and contains operational recommendations to government staff in reviewing water licence applications. Water allocation plans are useful because they provide context of water availability and water demand. This, in turn, supports consistent and timely decision making and promotes sustainability of the resource and security of existing water rights. Water allocation plans can be updated to include groundwater now that licensing of groundwater is in force. MBWD should consider discussing with FLNR the benefit and feasibility of updating the Shawnigan-Goldstream Water Allocation Plan (ENV, 2006) to include Aquifers 206 and 207.

It is also common practice for an FLNR water manager to register a water allocation restriction for a specific stream (<https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-licensing-rights/water-allocation-restrictions>). Water allocation restrictions have been registered for thousands of streams to inform government staff about water availability issues with a specific stream. A water allocation restriction signals issues with a specific water source to staff when reviewing applications for new uses. There are five types of water allocation restrictions:

**Refused No Water** - a previous application for a water licence was refused because there was insufficient water to grant the application.

**Possible Water Shortage** - a source is nearing the Fully Recorded stage and there is the potential for periods of insufficient water.

**Fully Recorded** - based on the information available, no further licences should be considered.

**Fully Recorded except for...** - based on the information available, no further licences should be considered except for licences for the specified purposes and/or quantities.

**Office Reserve** - this specialized comment should be taken into consideration before making any water allocation decisions regarding this source.

The concept of a water allocation restriction appears to apply equally to streams and aquifers. However, to-date no water allocation restriction has been registered for an aquifer, likely because groundwater licensing in BC is still in its infancy. MBWD should consider discussing with FLNR the benefit and appropriateness of a water allocation restriction being registered for Aquifer 206.

### 7.1.1 Collaborate to improve the water budgets for Aquifers 206 and 207

MBWD should continue to collaborate with the provincial ministries (ENV and FLNR) to continually help improve the water budgets for Aquifers 206 and 207. This would be mutually beneficial as improvement in understanding Aquifers 206 and 207 supports long-term sustainability of the local groundwater supply.

## 8. ACKNOWLEDGEMENTS

We thank the Mill Bay Waterworks District for funding this study. We also thank Klaus Rathfelder, Water Sustainability and Protection Branch, BC Ministry of Environment and Climate Change Strategy for collaboration, including access to geological cross-sections and groundwater level maps, SLR's water budget, as well as discussions throughout the study regarding our conceptual understanding of Aquifers 206 and 207.

## 9. REFERENCES

- Allen, D., 1999. *An assessment of the methodologies used for analyzing hydraulic test data from bedrock wells in British Columbia – Final report*. Ministry of Environment, Lands and Parks and Simon Fraser University. 91 pp.
- Associated Engineering, 2017. *Master Plan and Works Program*. Report to Mill Bay Waterworks District.
- BC Ministry of Environment (ENV), 2006. *Shawnigan-Goldstream Water Allocation Plan*. Water Stewardship Division, Vancouver Island Region. 99 pp.
- BC Ministry of Environment, Lands and Parks (ENV), 1999. *Evaluating Long-Term Capacity for a Certificate of Public Convenience and Necessity*. A guidance document from Water Management Branch. 16 pp.
- BC Ministry of Environment (ENV), 1996. *Aquifer Classification Work Sheet*. Aquifer Reference Number 0206.
- BC Ministry of Environment (ENV), 1996. *Aquifer Classification Work Sheet*. Aquifer Reference Number 0207.
- Blythe, H.E., Rutter, N.W., Sankeralli, L.M., 1993. *Surficial Geology of the Shawnigan Lake Area (NTS 92a/12)*. BC Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey, Open File 1993-26, 1:50000-scale map.
- Carmichael, V. E., 2014. *Compendium of Re-evaluated Pumping Tests in the Cowichan Valley Regional District, Vancouver Island, British Columbia*. Environmental Sustainability Division, Ministry of Environment. 1178 pp.
- Cooper, H. H. and C. E. Jacob, 1946. A generalized graphical method for evaluating formation constants and summarizing a well field history. *Trans. Amer. Geophys. Union*, 27, p. 526-534.
- Cui, Y., Miller, D., Schiarizza, P., Diakow, L.J. 2017. *British Columbia Digital Geology*. British Columbia Ministry of Energy, Mines and Petroleum Resources, British Columbia Geological Survey Open File 2017-8
- E. Livingston Associates – Consulting Groundwater Geologists (ELA), 1977. *Groundwater Exploration Program*. Unpublished report for Mill Bay Waterworks District. 16 pp.
- Freeze, R. A., and J. A. Cherry, *Groundwater*. Prentice Hall Inc., New Jersey, 1979.
- Gringarten, A. C., H. J. Ramey, and R. Raghaven, 1975. Applied pressure analysis for fractured wells. *J. Petrol. Techn.*, p. 887-892.

- Gringarten, A. C. and P. A. Witherspoon, 1972. A method of analyzing pump test data from fractured aquifers. In *Int. Soc. Rock Mechanics and Int. Ass. Eng. Geol.*, Proceedings of the Symposium on Rock Mechanics, Vol. 3-B, p. 1-9.
- Halstead, E.C, 1965. *Surficial Geology of Duncan and Shawnigan Map-Areas, British Columbia*. Paper 65-24. Geological Survey of Canada. Department of Mines and Technical Surveys.
- Harris, M. and S. Usher, 2017. *Preliminary Groundwater Budgets, Cobble Hill / Mill Bay Area, Vancouver Island, B.C.*, Water Science Series No. 2017-01, Ministry of Environment, 248 pp.
- Hodge Hydrogeology Consulting (HHC), 2006. *Mill Bay Waterworks District New Well 783.*, Unpublished report to Mill Bay Waterworks District. 35 pp.
- Lee, S., Wolberg, G., Shin, S.Y. 1997. Scattered Data Interpolation with Multilevel B-Splines. *IEEE Transactions on Visualisation and Computer Graphics*. Vol. 3, No. 3.
- Lowen Hydrogeology Consulting (LHC), 2003. *Well Drilling and Capacity Testing for the Deloume Road Subdivision*. Unpublished report to 613711 B.C. Ltd. 6 pp.
- Lowen Hydrogeology Consulting (LHC), 2005. *Mill Bay Waterworks District Well 2004-01*. Unpublished report to Mill Bay Waterworks District. 26 pp.
- Lowen Hydrogeology Consulting (LHC), 2006. *687033 BC Ltd. Fraser McColl and Gerald Hartwig Well 06-1*. Unpublished report for Water Source Approval. 41 pp.
- Lowen Hydrogeology Consulting (LHC), 2007. *Well 07-01 687033 BC Ltd. Fraser McColl and Gerald Hartwig*. Report for Water Source Approval. 40 pp.
- Lowen Hydrogeology Consulting (LHC), 2009. *Re-assessment of MBWD well 1387 capacity considering Mill Springs well 21614 drawdown interference, Mill Bay, BC*. Unpublished report to 687033 BC Ltd. 6 pp.
- Lowen Hydrogeology Consulting (LHC), 2010. *Confirmation of Groundwater Quantity, Quality, and Effect on MBWD Well 1387 – Well 21614 located at the Mill Springs Subdivision, Mill Bay, BC*. Unpublished report to Gerald Hartwig. 38 pp.
- Lowen Hydrogeology Consulting (LHC), 2017. Unpublished letter dated March 10, 2017 to Mill Bay Waterworks District. 4 pp.
- Morgan, S. E. and D. M. Allen, 2018. *Geoscience BC Peace Project: Final Report*, GeoscienceBC Report 2018-13. Geoscience BC, 70 pp.
- Muller, J.E., *Geology of Vancouver Island*; Geological Survey of Canada, Open File 463, 1: 250,000, 1977.
- Rathfelder, K., 2018. Personal communications regarding geological cross-sections and surface water monitoring. Ministry of Environment and Climate Change Strategy.

- Renard, P., D. Glenz, and M. Mejias, 2009. Understanding diagnostic plots for well-test interpretation. *Hydrogeology Journal*, 17, p. 589-600.
- Terracon Geotechnique Ltd. (TGL), 1994. *Appendix B Terracon Geotechnique Ltd. Alpex-Mill Bay Production Wells February 1994 Summary Report*. Appendix of report to Alpex Development Corporation. 49 pp.
- Theis, C. V., 1935. The relation between the lowering of the piezometric and the rate and duration of discharge of a well using groundwater storage. *Trans. Amer. Geophys. Union*, 16, p. 519-524.
- Thurber Engineering Ltd (TEL), 2010. *Mill Bay Waterworks District TH87-1 (Well #785) Assessment Report*. Unpublished report to Mill Bay Waterworks District. 66 pp.
- Thurber Engineering Ltd (TEL), 2016a. *Mill Bay Waterworks District Operational Data for Wells 21614, 15603, 1387, 786*. Letter submitted to Mill Bay Waterworks District, January 12, 2016. 11 pp.
- Thurber Engineering Ltd (TEL), 2016b. *Well 786 Rehabilitation Summary*. Unpublished report to Mill Bay Waterworks District.. 6 pp.
- Vrba, J. and A. Lipponen, 2007. *Groundwater resources sustainability indicators*. UNESCO, IHP-VI Series on Groundwater No. 14, 115 pp.
- Wei, M., 1987. *Potential Impact of Gravel Removal on Mill Bay Spring Sources*. Memorandum to A.P Kohut. Province of British Columbia. Ministry of Environment and Parks. Water Management Branch.
- Western Water Associates Ltd (WWAL), 2017a. *Well Assessment: Mill Bay Waterworks District Deer Park Supply Well (WIN 13286)*. Unpublished report to Mill Bay Waterworks District. 65 pp.
- Western Water Associates Ltd (WWAL), 2017b. *MBWD 2016 Supply Well Test Pumping Program Results*. Unpublished report for Mill Bay Waterworks District. 28 pp.
- Western Water Associates Ltd (WWAL), 2017c. *Well 21614 Rehabilitation and 2017 Test Pumping Results*. Unpublished report for Mill Bay Waterworks District. 11 pp.

## 10. GLOSSARY

**Available drawdown:** The total length of water column in a well (in metres or feet) that can be drawn down by pumping. The amount of available drawdown in a well is one of the factors affecting the capacity of the well to produce water when the well is pumped.

**B-Spline:** A spatial data interpolation technique.

**Calcareous:** Containing calcium bicarbonate; chalky.

**Carbonate rocks:** A type of sedimentary rock comprising minerals like calcite (forming limestone) and dolomite (forming dolostone). Carbonate rocks can dissolve over time by percolating water that is slightly acidic.

**Coarse-textured:** Soil or surficial geological deposit comprising coarse-grained sediments like sand and gravel.

**Crystalline rock:** Igneous or metamorphic rocks such as granite or basalt. Groundwater in crystalline rocks generally occurs in fractures in the rock.

**Database:** A collection of records and files that are logically organized to assist with the query and analysis of data.

**Digital elevation model (DEM):** 3-Dimensional computer graphic representation of the land surface.

**Down-wasting:** Thinning of a glacier caused by melting of the ice.

**Drawdown:** The difference (in metres or feet) between the static water level and the pumping water level at a particular location.

**Epikarst:** A weathered zone of enhanced porosity on or near the surface or at the soil/bedrock contact of many karst landscapes. The epikarst is essentially the upper boundary of a karst system.

**Fine-textured:** Soil or surficial geological deposit comprising fine-grained sediments like silt and clay.

**Geometric mean:** The geometric mean is defined as the  $n$ th root of the product of  $n$  numbers. For example, the geometric mean of the three numbers 1, 3, and 5 is the cube-root of the product of those three numbers (geometric mean of 2.47). In hydrogeology, geometric mean is often a more representative “average” of parameters like transmissivity or permeability than the arithmetic average.

**Glaciofluvial deposit:** Sediments (primarily sand, gravel, some silt) deposited by a meltwater river or stream associated with glaciation.

**Glaciomarine deposit:** Sediments (primarily silt and clay) deposited in a marine environment during glacial times.

**Granodiorite:** An igneous rock similar to granite but containing more magnesium and iron minerals than granite.

*Groundwater flow divide:* The boundary between two groundwater basins where groundwater flows in one direction on one side of the divide and in another direction on the other side of the divide.

*Heterogeneous:* In relation to geology, spatially diverse and varied in geological characteristics.

*Hydraulic gradient:* The amount the groundwater level decreases over a specific distance in a specific direction (e.g., vertical hydraulic gradient; horizontal hydraulic gradient). Hydraulic gradient is usually expressed as a dimensionless fraction (e.g., 0.0005).

*Ice-rafted materials:* Sediments carried by ice drifting over a body of water that is eventually deposited in the body of water as the ice melts.

*Ideal aquifer:* An aquifer in which the pumping water level draws down at a rate that reflects radial flow to the well.

*Intrusive rock:* Igneous rock formed from magma that cooled and hardened beneath the earth. Granite is a type of intrusive igneous rock.

*Light Detection and Ranging (LIDAR):* A remote sensing technique that uses light in the form of a pulsed laser to measure distances to the earth surface to map the earth's surface.

*Karst:* Topography formed from the dissolution of soluble rocks such as limestone, dolostone, and gypsum by water, resulting in formation of sinkholes, caves and underground channels.

*Kettle:* A large pothole (can be over 1 Km in diameter) formed by melting of a large block of ice left behind by a glacier and lodged in a glaciofluvial deposit.

*Kame deposit:* Sand, gravel and till deposited on depression surfaces of a melting glacier. As the glacier melts, the sand, gravel, till are then left stranded on the land surface forming irregularly shaped hills, mounds, ridges.

*Marine deposit:* Sediments (primarily silt and clay) deposited in a marine environment.

*Morainal deposit:* Unsorted unconsolidated sediments (sand, gravel, clay, silt, boulders) carried and deposited by a glacier.

*Overburden:* A general field term referring to undifferentiated unconsolidated soils or sediments overlying bedrock.

*Plutonic:* Synonymous with “intrusive”.

*Porosity (n):* The ratio of the volume of pore spaces within a total volume of soil or rock. Porosity is usually expressed as a percentage (e.g., 30%) or fraction (e.g., 0.30).

*Primary porosity (n):* Pore spaces that exist when the soil or rock was first formed (like pores in sand being deposited in a stream).

*Pumping test:* A flow test of a well in which the well is pumped and the quantity of water pumped, pumping water levels and recovery water levels are measured

- (a) to provide an estimate of the capacity of the well to produce groundwater, and
- (b) to assess aquifer characteristics (legal definition from the *Water Sustainability Act*).

*Radius of influence:* The area (commonly assumed to be circular) around a pumping well that experiences drawdown in the groundwater level.

*Recharge (R):* Process by which water (e.g., from infiltration of precipitation) enters and replenishes an aquifer over a specified period of time. Recharge can be reported as volume per time period (e.g., m<sup>3</sup>/year) or depth (volume per area) per time period (e.g., mm/year).

*Specific capacity:* The ratio of the pumping rate per unit of drawdown, commonly expressed in litres per second per metre of drawdown or gallons per minute per foot of drawdown. Specific capacity reflects the productivity of the aquifer and efficiency of the production well.

*Static water level (SWL):* Distance (in metres or feet) from the top of the production casing or the surface of the ground to the groundwater level in the well, when the groundwater level is not affected by pumping activities in the well (legal definition from the *Water Sustainability Act*).

*Storativity (S):* Volume of water stored or released from a column of aquifer with unit cross section under unit change in groundwater level. Storativity determines how quickly (or slowly) an aquifer responds to hydraulic changes and is reported as a dimensionless number (e.g., 0.0001).

*Stratigraphy:* The study of the relationship of different geological units within an area, with respect to their age and spatial distribution.

*Surficial geologic deposit:* A geological deposit comprising soil, silt, sand, gravel and other unconsolidated sediments.

*Terrain Resource Inventory Mapping (TRIM):* A set of 3-D digital files produced by the Province of BC for GIS mapping.

*Till deposit:* Primarily a mixture of clay, silt, sand, gravel and boulders ranging widely in size and shape deposited directly by and underneath a glacier. Synonymous with “*morainal deposit*”.

*Transmissivity (T):* The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity is commonly expressed as metres squared per second or day, feet squared per second or day, or gallons per day per foot. Transmissivity reflects the permeability of the aquifer integrated over the thickness of the aquifer.

*Unconsolidated deposit:* A geological deposit comprising loose sediments. Synonymous with “*Surficial geologic deposit*”.

*Well identification number:* The number on the well identification plate issued by the Province of BC and attached to a well.

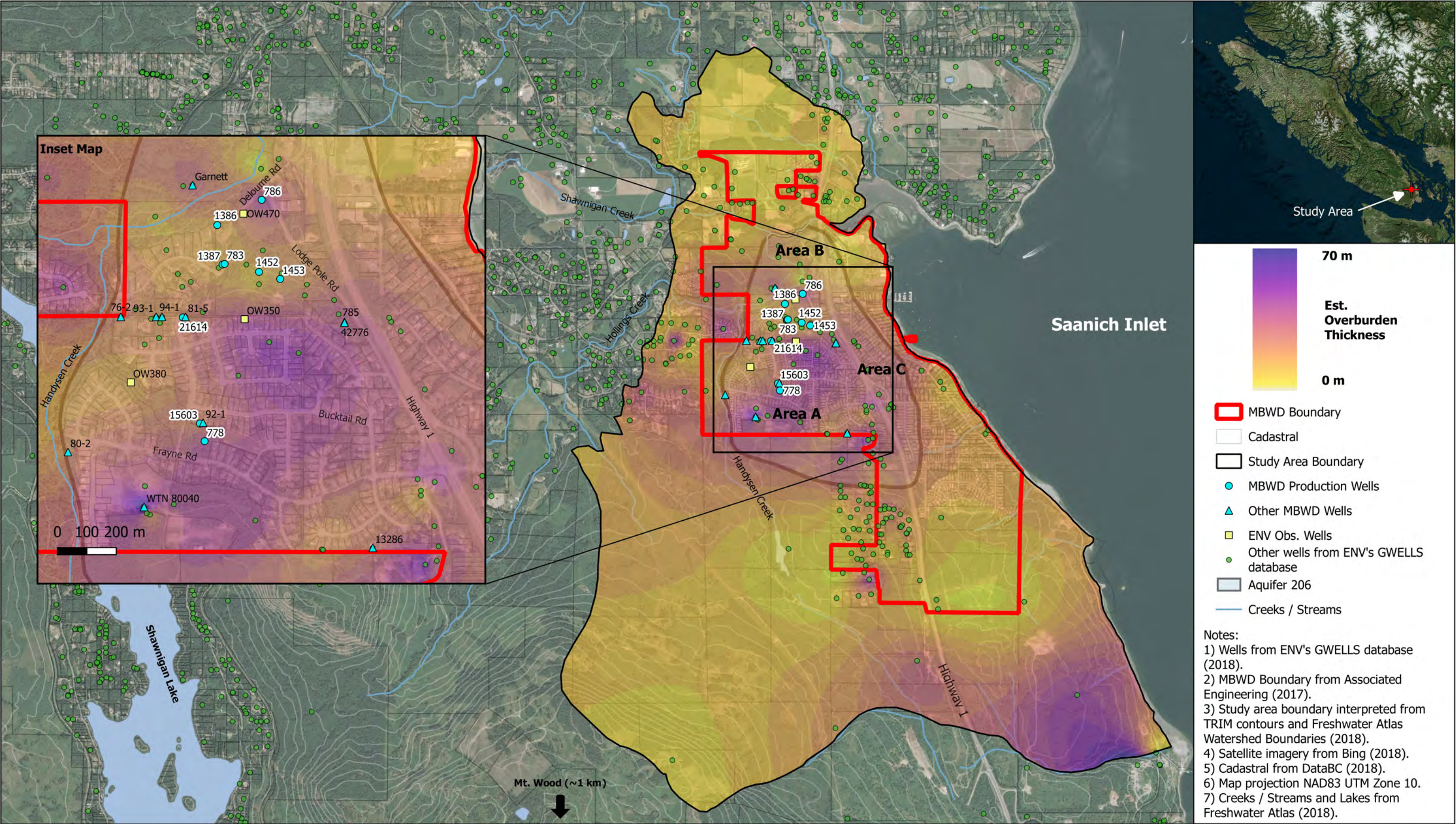
*Well interference:* Drawdown in a well caused by pumping in a nearby well.

*Well tag number:* The file number assigned to the record of a specific well in the Province of BC's GWELLS database. Well tag number is a legally defined term in the Groundwater Protection Regulation.

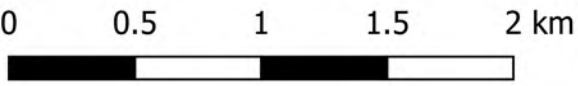
## **Western Water Associates Ltd.**

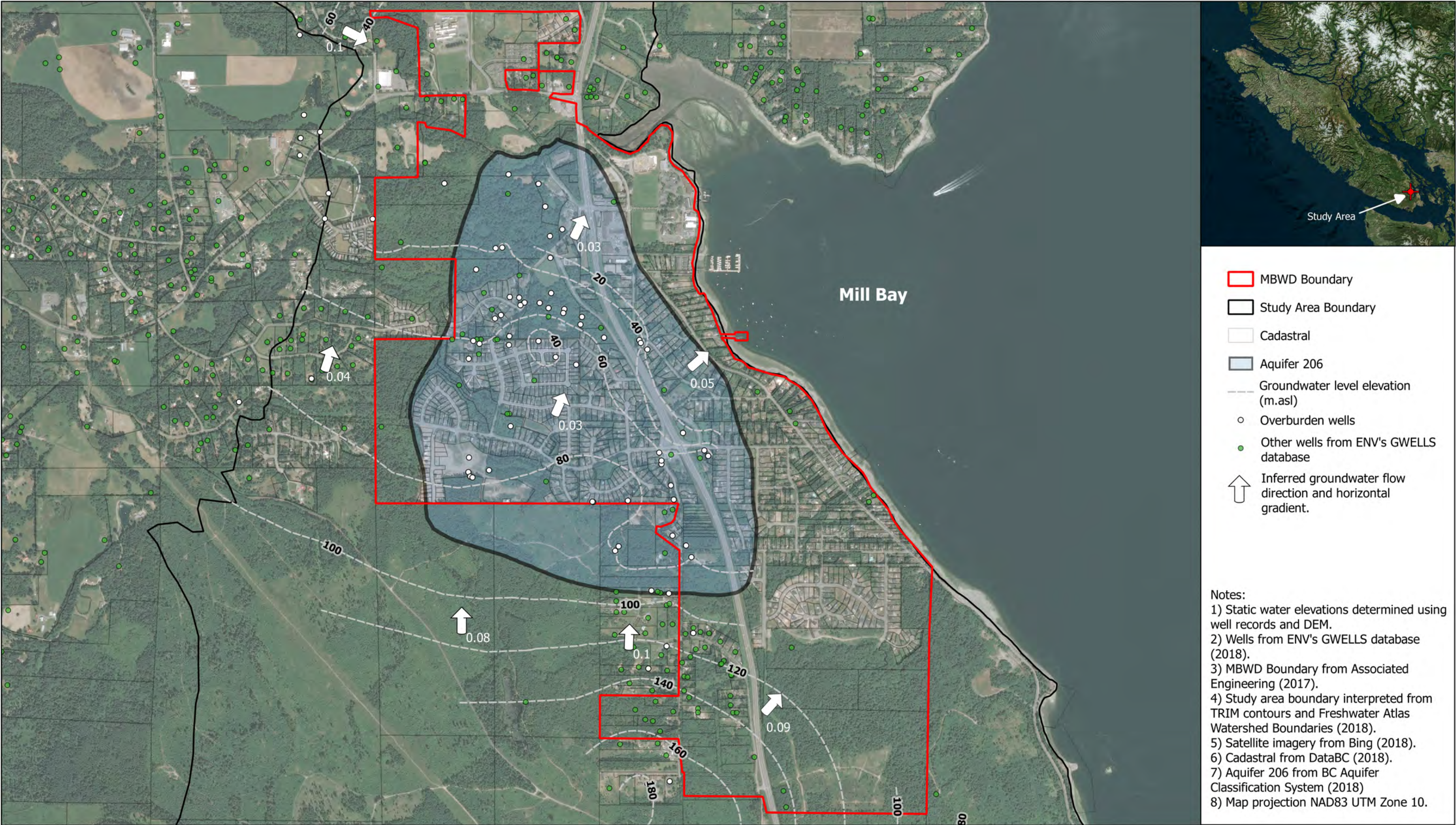
### **Standard Report Limitations**

1. This Document has been prepared for the particular purpose outlined in the work scope that has been mutually agreed to with the Client.
2. The scope and the period of service provided by Western Water Associates Ltd are subject to restrictions and limitations outlined in subsequent numbered limitations.
3. A complete assessment of all possible conditions or circumstances that may exist at the Site or within the Study Area referenced, has not been undertaken. Therefore, if a service is not expressly indicated, it has not been provided and if a matter is not addressed, no determination has been made by Western Water Associates Ltd. in regards to it.
4. Conditions may exist which were undetectable given the limited nature of the enquiry that Western Water Associates Ltd. was retained to undertake with respect to the assignment. Variations in conditions may occur between investigatory locations, and there may be special conditions pertaining to the Site, or Study Area, which have not been revealed by the investigation and which have not therefore been taken into account in the Document. Accordingly, additional studies and actions may be required.
5. In addition, it is recognised that the passage of time affects the information and assessment provided in this Document. Western Water Associates Ltd's opinions are based upon information that existed at the time of the production of the Document. It is understood that the Services provided allowed Western Water Associates Ltd to form no more than an opinion of the actual conditions of the Site, or Study Area, at the time the site was visited and cannot be used to assess the effect of any subsequent changes in the quality of the Site, or Study Area, nor the surroundings, or any laws or regulations.
6. Any assessments made in this Document are based on the conditions indicated from published sources and the investigation described. No warranty is included, either expressed or implied, that the actual conditions will conform exactly to the assessments contained in this Document.
7. Where data supplied by the Client or other external sources, including previous site investigation data, have been used, it has been assumed that the information is correct unless otherwise stated.
8. No responsibility is accepted by Western Water Associates Ltd for incomplete or inaccurate data supplied by others.
9. The Client acknowledges that Western Water Associates Ltd may have retained sub-consultants affiliated to provide Services. Western Water Associates Ltd will be fully responsible to the Client for the Services and work done by all of its sub-consultants and subcontractors. The Client agrees that it will only assert claims against and seek to recover losses, damages or other liabilities from Western Water Associates Ltd.
10. This Document is provided for sole use by the Client and is confidential to it and its professional advisers. No responsibility whatsoever for the contents of this Document will be accepted to any person other than the Client. Any use which a third party makes of this Document, or any reliance on or decisions to be made based on it, is the responsibility of such third parties. Western Water Associates Ltd. accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this Document.

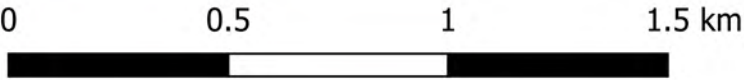


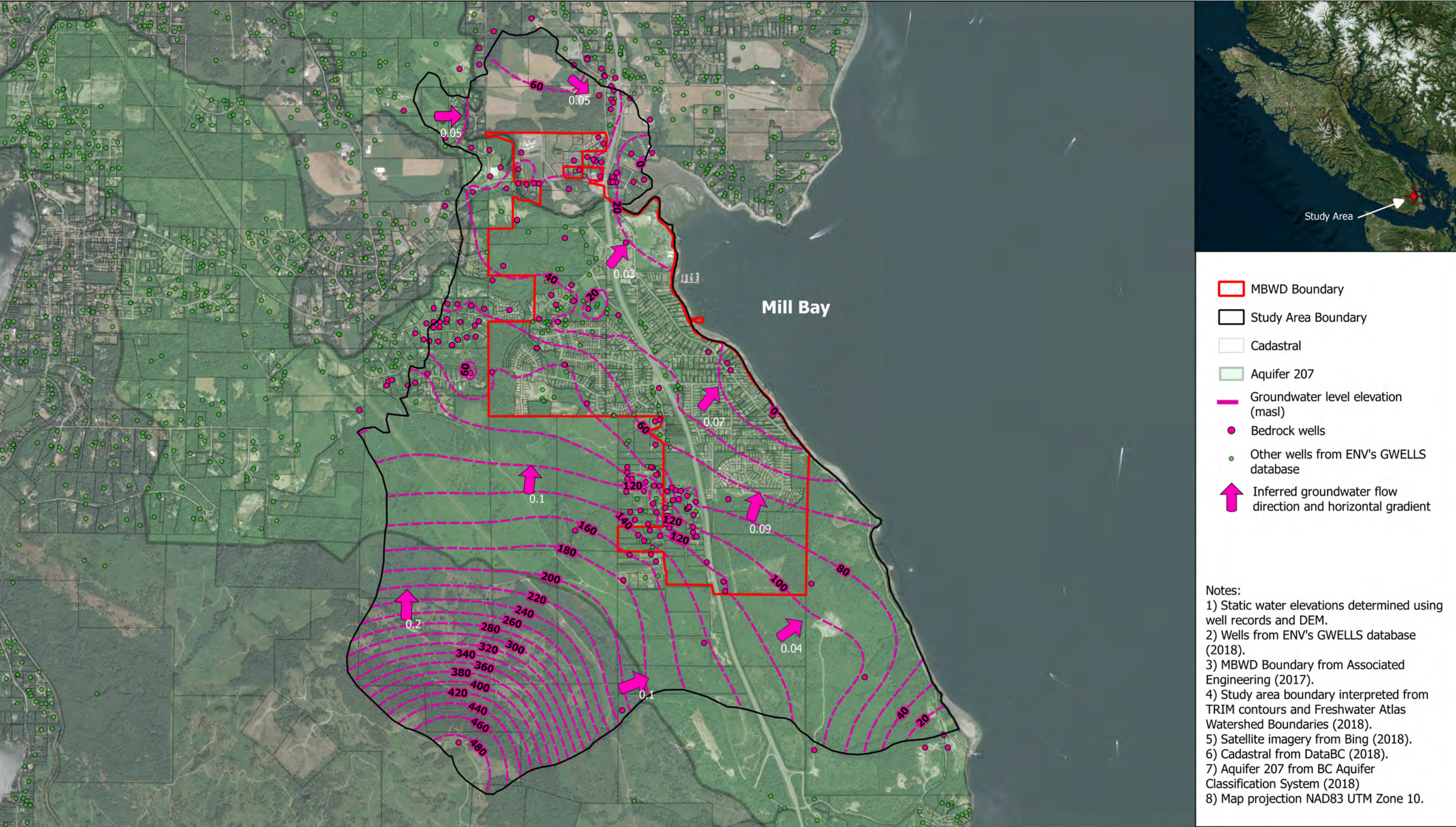
|                                                                                                                                   |                                                       |                            |                          |
|-----------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------|----------------------------|--------------------------|
| <div>MBWD Local Aquifer Study</div> <div></div> | TITLE<br><b>Map 1.</b> Estimated Overburden Thickness |                            |                          |
|                                                                                                                                   | DRAWN<br>T.Sivak                                      | DATE<br>October 22nd, 2018 | PROJECT NO.<br>16-076-02 |
|                                                                                                                                   | CHECKED<br>M.Wei                                      | SCALE<br>See Bar Scale     | DWG NO.                  |
|                                                                                                                                   | REVIEWED                                              | FILE NO.                   | FIGURE VERSION NO.       |





|                          |          |         |          |                                                            |                       |
|--------------------------|----------|---------|----------|------------------------------------------------------------|-----------------------|
| MBWD Local Aquifer Study |          | TITLE   |          | Map 2a. Reported Groundwater Level Elevation in Overburden |                       |
|                          | DRAWN    | T.Sivak | DATE     | September 28, 2019                                         | PROJECT NO. 16-076-02 |
|                          | CHECKED  | M.Weir  | SCALE    | See Bar Scale                                              | DWG NO.               |
|                          | REVIEWED |         | FILE NO. |                                                            | FIGURE VERSION NO.    |



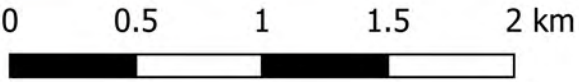


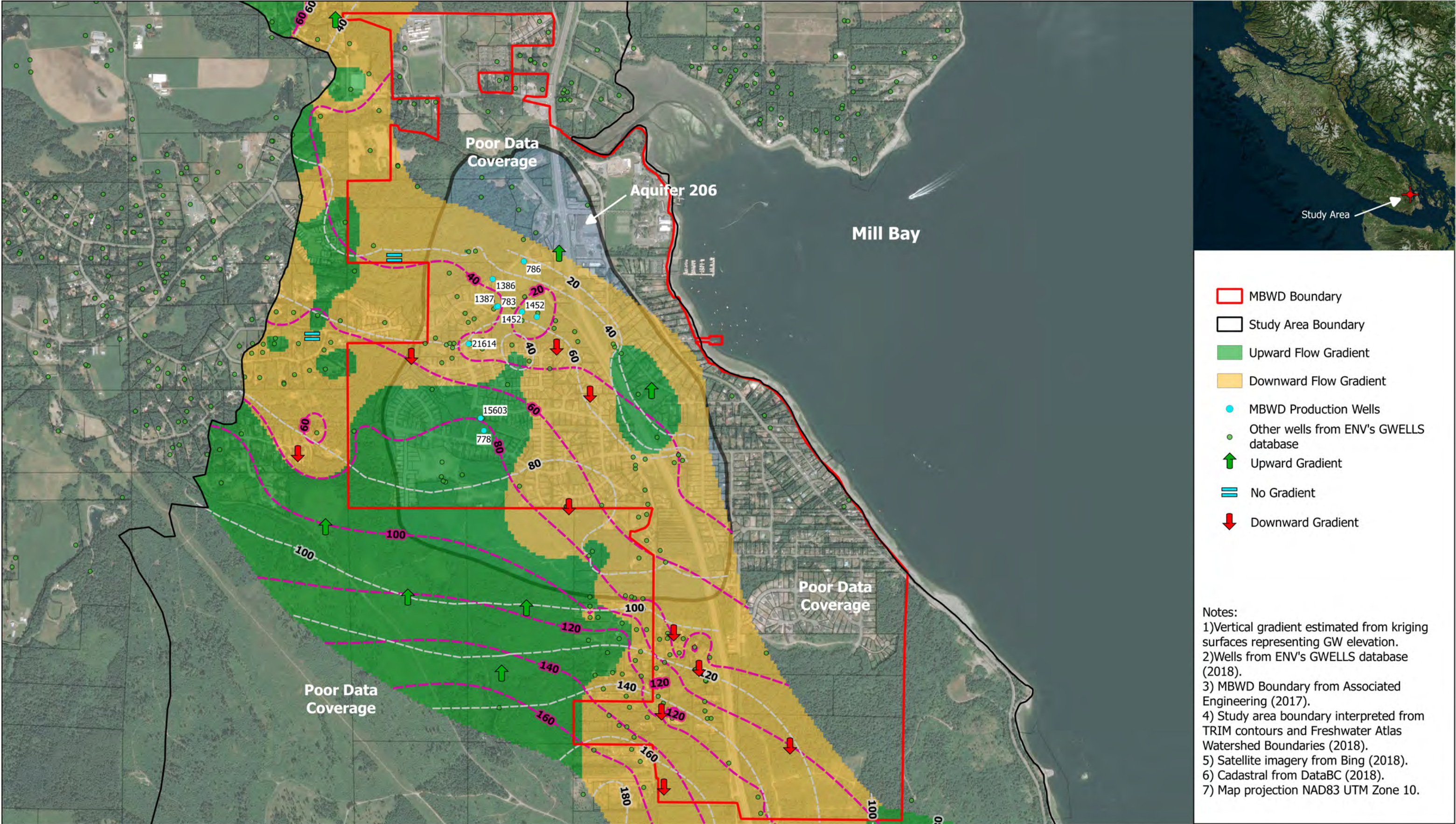
- MBWD Boundary
- Study Area Boundary
- Cadastral
- Aquifer 207
- Groundwater level elevation (masl)
- Bedrock wells
- Other wells from ENV's GWELLS database
- Inferred groundwater flow direction and horizontal gradient

Notes:

- 1) Static water elevations determined using well records and DEM.
- 2) Wells from ENV's GWELLS database (2018).
- 3) MBWD Boundary from Associated Engineering (2017).
- 4) Study area boundary interpreted from TRIM contours and Freshwater Atlas Watershed Boundaries (2018).
- 5) Satellite imagery from Bing (2018).
- 6) Cadastral from DataBC (2018).
- 7) Aquifer 207 from BC Aquifer Classification System (2018)
- 8) Map projection NAD83 UTM Zone 10.

|                          |  |          |  |                                                         |  |
|--------------------------|--|----------|--|---------------------------------------------------------|--|
| MBWD Local Aquifer Study |  | TITLE    |  | Map 2b. Reported Groundwater Level Elevation in Bedrock |  |
| DRAWN T. Sivak           |  | DATE     |  | September 28th, 2018                                    |  |
| CHECKED M.Weir           |  | SCALE    |  | See Bar Scale                                           |  |
| REVIEWED                 |  | FILE NO. |  | PROJECT NO. 16-076-02                                   |  |
|                          |  |          |  | DWG NO.                                                 |  |
|                          |  |          |  | FIGURE VERSION NO.                                      |  |

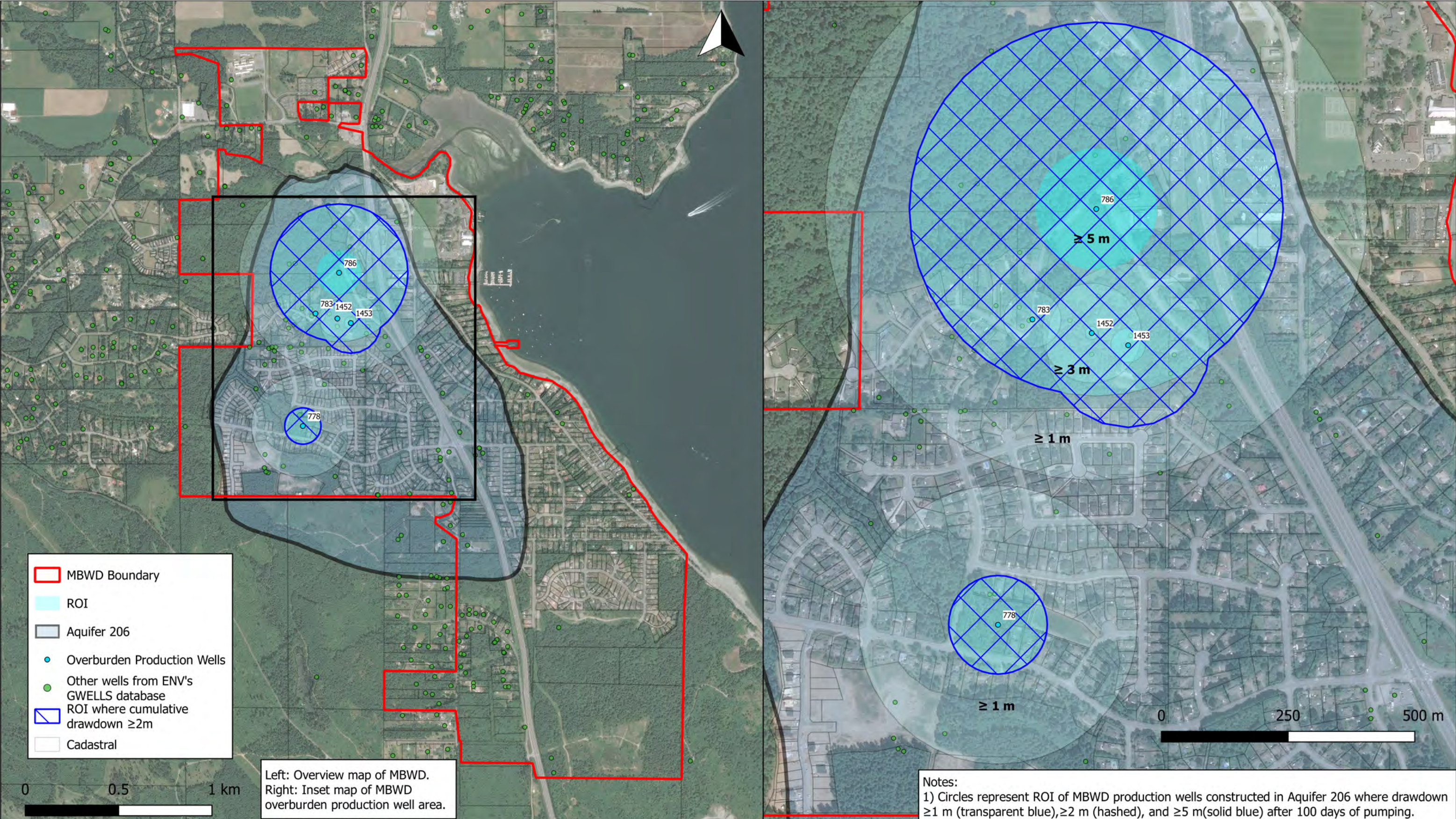




- MBWD Boundary
- Study Area Boundary
- Upward Flow Gradient
- Downward Flow Gradient
- MBWD Production Wells
- Other wells from ENV's GWELLS database
- Upward Gradient
- No Gradient
- Downward Gradient

Notes:  
1)Vertical gradient estimated from kriging surfaces representing GW elevation.  
2)Wells from ENV's GWELLS database (2018).  
3) MBWD Boundary from Associated Engineering (2017).  
4) Study area boundary interpreted from TRIM contours and Freshwater Atlas Watershed Boundaries (2018).  
5) Satellite imagery from Bing (2018).  
6) Cadastral from DataBC (2018).  
7) Map projection NAD83 UTM Zone 10.

|                          |          |                                                           |          |                        |  |                      |                    |           |
|--------------------------|----------|-----------------------------------------------------------|----------|------------------------|--|----------------------|--------------------|-----------|
| MBWD Local Aquifer Study |          | TITLE<br><b>Map 3.</b> Vertical Groundwater Flow Gradient |          | <div>00.511.5 km</div> |  |                      |                    |           |
|                          | DRAWN    | T. Sivak                                                  | DATE     |                        |  | September 28th, 2018 | PROJECT NO.        | 16-076-02 |
|                          | CHECKED  | M.Wei                                                     | SCALE    |                        |  | See Bar Scale        | DWG NO.            |           |
|                          | REVIEWED |                                                           | FILE NO. |                        |  |                      | FIGURE VERSION NO. |           |



|                                                                                    |                          |          |          |                      |                                                                 |           |
|------------------------------------------------------------------------------------|--------------------------|----------|----------|----------------------|-----------------------------------------------------------------|-----------|
|  | MBWD Local Aquifer Study |          | TITLE    |                      | Map 4a. Radius of Influence (ROI) for MBWD Wells in Aquifer 206 |           |
|                                                                                    | DRAWN                    | T. Sivak | DATE     | September 25th, 2018 | PROJECT NO.                                                     | 16-076-02 |
|                                                                                    | CHECKED                  | M. Wei   | SCALE    | See Bar Scales       | DWG NO.                                                         |           |
|                                                                                    | REVIEWED                 |          | FILE NO. |                      | FIGURE VERSION NO.                                              |           |

Notes:

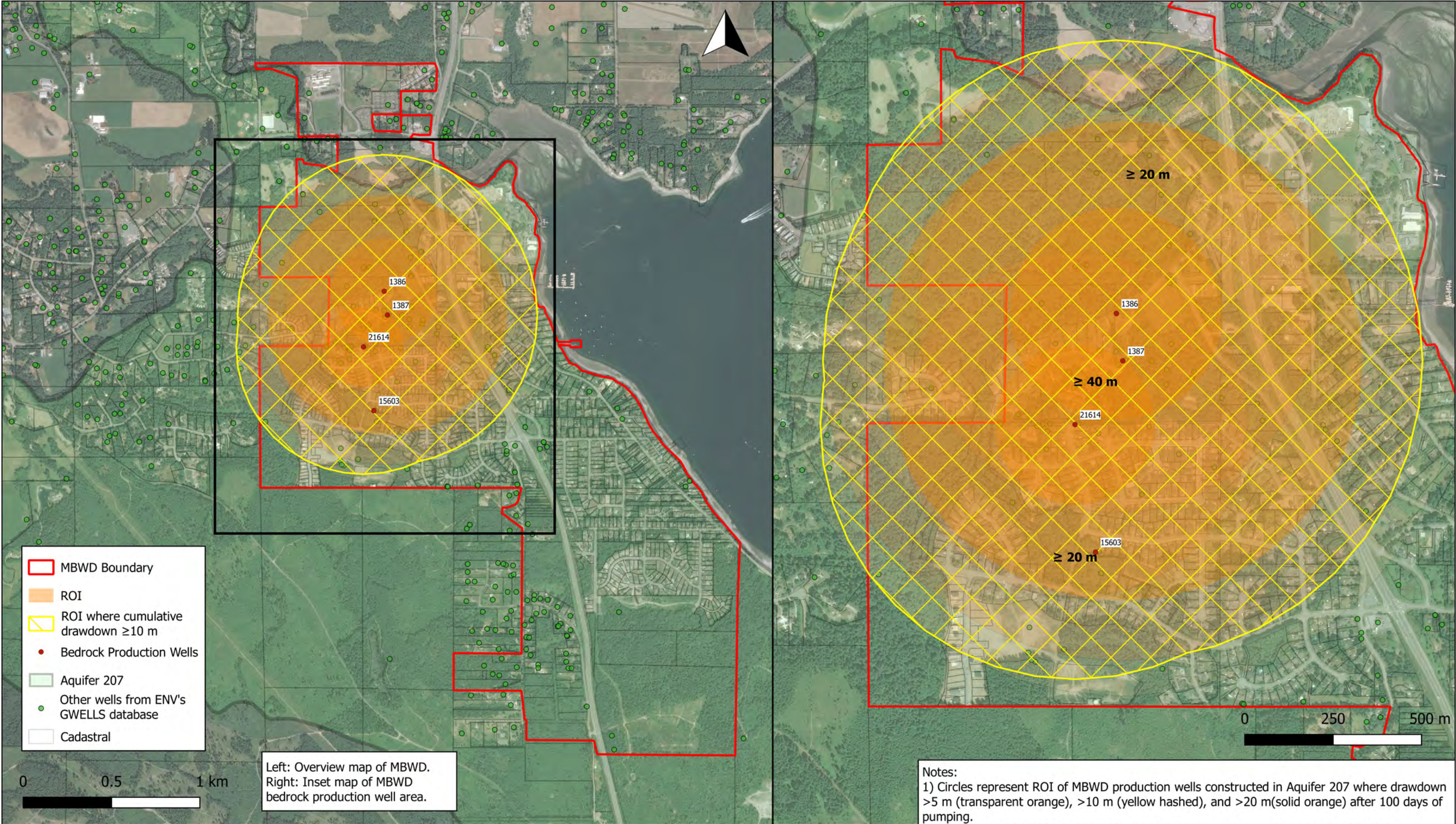
1) Circles represent ROI of MBWD production wells constructed in Aquifer 206 where drawdown  $\geq 1$  m (transparent blue),  $\geq 2$  m (hashed), and  $\geq 5$  m (solid blue) after 100 days of pumping.

2) ROI calculated using Cooper-Jacob (1946). Q and T values used in calculations from operational data (Associated Engineering, 2017) and from pump tests conducted by others. See report text for specific sources.

3) Drawdown values are cumulative where ROI for wells overlap.

4) See Figures 1-4 for other data sources.

5) Map projection NAD83 UTM Zone 10.



|                          |          |                                                                 |                    |                    |
|--------------------------|----------|-----------------------------------------------------------------|--------------------|--------------------|
| MBWD Local Aquifer Study |          | Map 4b. Radius of Influence (ROI) for MBWD Wells in Aquifer 207 |                    |                    |
|                          | DRAWN    | T.Sivak                                                         | DATE               | September 26, 2018 |
|                          | CHECKED  | M.Wei                                                           | SCALE              | See Bar Scales     |
|                          | REVIEWED |                                                                 | FILE NO.           |                    |
|                          |          |                                                                 | PROJECT NO.        | 16-076-02          |
|                          |          |                                                                 | DWG NO.            |                    |
|                          |          |                                                                 | FIGURE VERSION NO. |                    |



Groundwater Supply Development and Management

Source Water Assessment and Protection

Well Monitoring & Maintenance

Environmental & Water Quality Monitoring

Storm & Wastewater Disposal to Ground

Groundwater Modeling

Aquifer Test Design and Analysis

Geothermal / Geoexchange Systems

Policy and Guideline Development

Applied Research

Rural Subdivision Services

Environmental Assessment & Permitting