EARTH SCIENCES
SIMON FRASER UNIVERSITY

OBSERVATION WELL TESTING AND RECHARGE CHARACTERIZATION OF THE OKANAGAN BASIN, BC

Final Report

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EXECUTIVE SUMMARY

Concern about quantities, quality and sustainability of groundwater resources within the Okanagan Valley, British Columbia prompted the establishment of a joint Federal Provincial initiative Ground Water Assessment of the Okanagan Basin (GAOB). This study constitutes one project listed in the GAOB scientific research program. The study is a preliminary investigation aimed at characterizing the aquifer media surrounding provincial monitoring wells in Okanagan Valley using slug testing methods, analyzing groundwater level fluctuations using a cumulative precipitation departure (CPD) graph, and using the hydrographs to estimate recharge using the water table fluctuation (WTF) method. The hydraulic conductivities determined from slug testing range between ~10^{-7} m/s for silty clay aquifers, and ~10^{-3} m/s for gravel and sand aquifers. The values obtained from slug testing correspond well with published values of hydraulic conductivities. The cumulative precipitation departure method indicated that six wells in the study area are primarily recharged by precipitation. The water table fluctuation method indicated that mean monthly recharge rates range between 24 mm and 318 mm, although, the usefulness of the each value may depend on the adherence to assumptions in the WTF method.

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1. INTRODUCTION

1.1. RECHARGE

Recharge is defined as the water that percolates vertically through soil and returns to the water table. The aim of most recharge characterization studies is to estimate the amount of groundwater that becomes available each year through recharge. When a water budget is calculated, recharge is the amount of water that can be used without the diminishing groundwater supply through anthropogenic means. Recharge estimation is essential for groundwater flow models and efficient resource management.

There are three main types of recharge: (1) Direct recharge occurs by vertical percolation through the vadose zone and is subject to evapotranspiration loss and soil-moisture deficits; (2) Indirect recharge involves the transfer of water from surface water channels to groundwater through the channel boundary; and (3) Localized recharge requires water to travel the furthest distance through joints, depressions and rivulets to the water table. Estimates of direct recharge are the most obtainable within the scope of this study because of the direct dependence of recharge on precipitation. An aquifer is directly recharged if the elevation of the water table responds sympathetically with the climate data. Observation wells that monitor the natural level of the water table can be used to estimate the recharge, if the location can be deemed under the influence of direct recharge only.

1.2. BACKGROUND

The Okanagan Valley is located in the southern interior of British Columbia, situated around Okanagan Lake (Figure 1.1). The valley is approximately 160 km in length and encompasses approximately 8200 km^2 of land surrounding Okanagan Lake and Okanagan River (Okanagan Basin Water Board, 2000).

The Okanagan has a dry continental climate as the Valley sits in the rain-shadow of the Coast and Cascade Mountain Ranges. The semi-arid climate receives approximately 30cm of precipitation per year; of this 85% is lost through evapotranspiration and evaporation from local lakes (Environment Canada and University of British Columbia

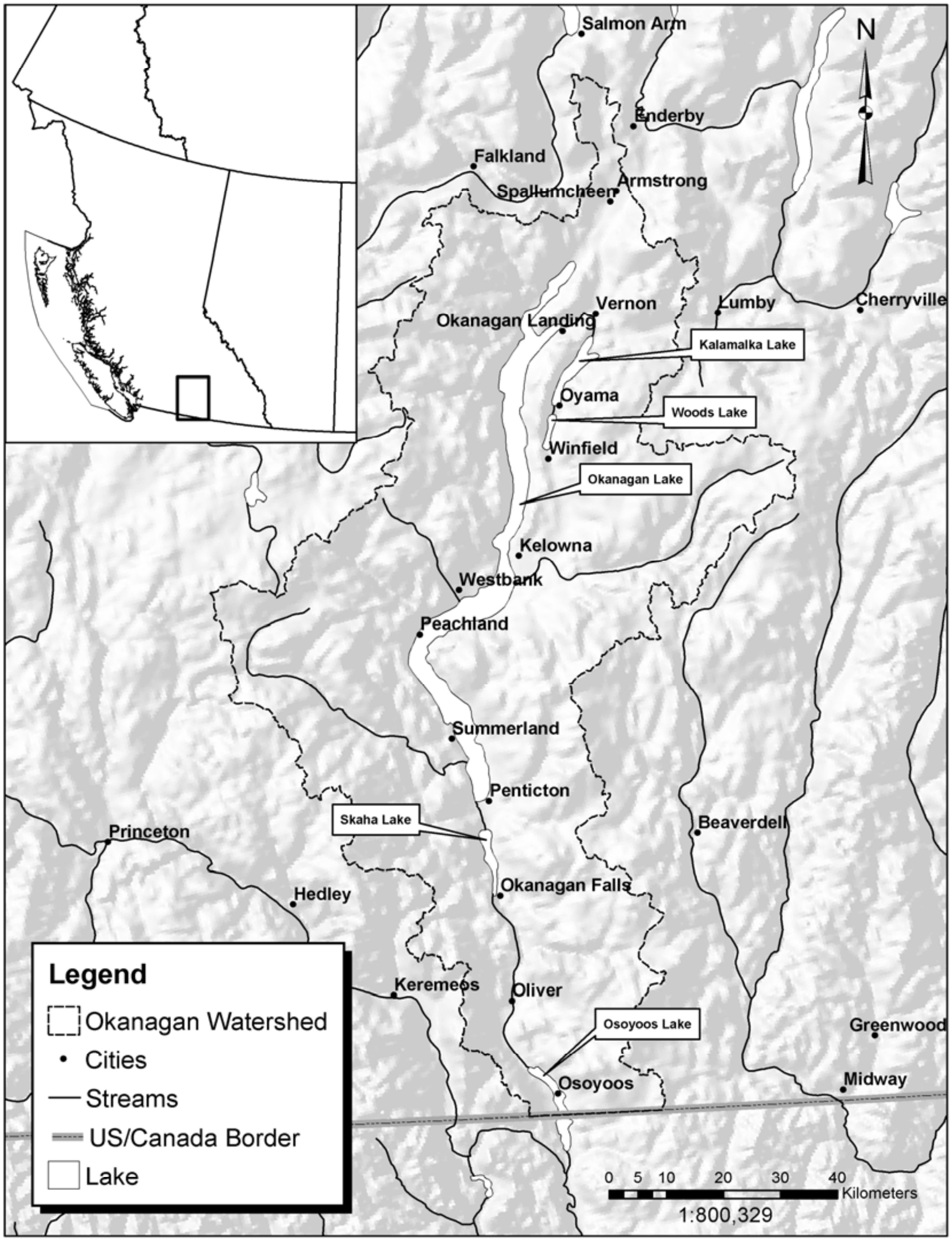
(UBC), 2001). Okanagan Lake is the largest surface water feature, running the length of the Valley from north to south. However, the main water sources for the Okanagan are the tributary streams, which generally support good quality water.

The Okanagan Basin encompasses 13 municipalities, 3 regional districts, 4 First Nation communities and 59 “improvement” districts, all of which share responsibility in water delivery. Various water managers oversee more than 45 community watersheds, 6900 water licenses, and over 385,000 acre-feet in water allocations (Environment Canada and UBC, 2001). This has left very little leeway for further allocations as most streams are listed as either “fully recorded” or “water shortage”.

Over 1 million tourists visit the region each year (Environment Canada and UBC, 2001). Agriculture and farming have been part of the Okanagan since the 1850s, and today the Okanagan agricultural land use consists of cropland, fruit orchards, grapes, and pasture (Environment Canada and UBC, 2001). The rapid population growth in Central Okanagan (~125,000 in 1976 to >250,000 in 1999) has led to significant land use changes, specifically the loss of farmland. Between 1976 and 1996, the total area farmed has decreased from 80,428 ha to 78, 283 ha, likely due to urbanization (Statistics Canada, 1996).

In light of the growing population base, an important question has been raised in recent years concerning how water will be partitioned between agriculture and residential consumption. The answer depends on how much water is available for consumption. The problem gains further urgency in arid to semi-arid climates where aquifers are precious and vulnerable, such as the Okanagan. At present, groundwater usage is uncertain in the Okanagan, but as surface water resources are stretched to the limit of sustainability, conjunctive use of surface water and groundwater will likely be inevitable.

Figure 1.1 Map of study area showing the extent of the Okanagan Basin watershed in south central British Columbia, Canada.



1.3. PURPOSE OF STUDY

The research described in this report constitutes a small part in a larger project entitled Groundwater Assessment of the Okanagan Basin (GAOB). The GAOB project is a joint initiative between the British Columbia Ministry of Water, Land and Air Protection (BCWLAP) and the Geological Survey of Canada (GSC). Other members of the scientific working group include: Okanagan Basin Water Board, Interior Health Authority, BC Groundwater Association, Agriculture Canada, Canada Centre of Excellence for Water, Simon Fraser University (SFU), Okanagan University College OUC) and others. The project team members aim to address issues surrounding groundwater resources within Okanagan Basin, dealing with many aspects of science, growth and management planning, and climate change. The primary purpose of this research project is to contribute to the hydrogeological mapping and recharge estimation initiatives in the Okanagan region. The project aims to examine observation well data and describe major climate-induced recharge variations along the length of Okanagan Valley. In addition, a new study was initiated to collect and analyze hydraulic data using slug testing methods.

1.4. STUDY OBJECTIVES

The specific objectives of the project are:

1. To derive estimates of the hydraulic conductivity of aquifer media encountered in the Okanagan region by:
    a. Undertaking a slug testing program in the Observation Well Network
    b. Providing training to MWLAP staff on the slug testing methodology/procedures and analysis

2. To provide an assessment of spatial trends in recharge in the Okanagan region by analyzing the water level data from the Observation Well Network.

1.5. OUTLINE OF REPORT

The introduction to the study area, including a brief review of the regional context, and a statement of the purpose and objectives of the study are described in Section 1. Section 2 discusses the sources of data used to conduct the slug testing program and describes climatic variation. The methodology employed for slug testing and the techniques used to analyze response data are described in Section 3. In Section 4, climate data are examined and used to characterize trends up the valley, and to determine which observation wells respond to precipitation. Section 5 uses the wells that respond to precipitation to quantify the amount of recharge in those aquifers.

1.6. ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support of BC Ministry Water, Land and Air Protection. In particular, Des Anderson and Trina Koch deserve many thanks for their help in conducting the slug tests. Thanks also to Vicki Carmichael and Kevin Ronneseth for providing access to observation well data and logistical information to complete the project. Thanks to Paul Whitfield (Environment Canada) for providing digital climate data files and technical advice. Thank you to the various contributors on the GAOB field trip (July 2004) who shared important information concerning groundwater in the Okanagan Valley.

2. REGIONAL CONTEXT AND DATA SOURCES

2.1. GEOLOGY

Many of the most prominent geologic features in the Okanagan Valley were formed during the Tertiary Period; however, some of the oldest rocks in British Columbia occur in Kelowna on the east side of Lake Okanagan (Roed, 1995). The Monashee Gneiss of the Shuswap Terrane is estimated to be 2.0 billion years old, and these banded metamorphic rocks form Rattlesnake Island located at the knee of Lake Okanagan. Grand Forks Gneiss also belongs to the Monashee Complex, and occurs east of Oliver. Other Proterozoic to Paleozoic rocks, including orthogneiss of the Shuswap Assemblage, can be found on the east side of Kalamalka Lake and Vernon (BCGS Geology Map, 2004). Roed (1995) has compiled a geologic column of the Okanagan Valley from work done by Church (1980) and Templemann-Kluit (1989). There are few persistent occurrences of Paleozoic rocks in the Okanagan Valley. Near Osoyoos, Anarchist Schist and greenschist, of the Mt. Kobau Metamorphic Suite, form the valley walls. The only other Paleozoic rocks in the valley are chert and siliceous argillite, of the Shoemaker Formation, near Vaseux Lake, and fine clastic sedimentary rocks, of the Harper Ranch Group, near Vernon. The Mesozoic Era is represented by Jurassic to Cretaceous age granitic intrusive rocks and Triassic to Jurassic Age volcanic and volcanoclastic rocks. The largest intrusive feature is the Okanagan Batholith that composes most of the bedrock on the east and west side of Penticton. Mesozoic volcanics of the Nicola Group occur near Peachland and Vernon.

The majority of Tertiary bedrock features are volcanic in origin. Most of the volcanic rocks belong to the Penticton Group of the Eocene epoch, and include the Kettle River, Springbrook, Marron, Marama White Lake and Skaha Formations (Church, 1980; 1981). Volcanic rocks belonging to the Kamloops Group are found west of Vernon, and are Eocene in age. The Penticton Group contains basaltic to rhyolitic lava flows, poryphitic dyke and sill structures, and volcanic conglomerate, breccia, sandstone and shales (Church and Hora, 1985). Younger basaltic volcanic rocks belonging to the Chilcotin Group (Miocene to Pliocene) are found east of Kalamalka Lake and Woods Lake.

Linear lakes oriented along faults are common in the BC interior. Okanagan Valley follows the trend of the Okanagan fault. A notable exception to this is the "knee" in Okanagan Lake where the Okanagan fault is dextrally offset by the Mission Creek Fault. The Okanagan fault was most active in the Eocene and coincided with Eocene volcanic activity that produced the rocks in the Penticton Group (Roed, 1995). The Okanagan fault is a normal fault that helped to create the horst and graben features in area and expose Precambrian rocks of the Monashee complex.

Surficial deposits in the Okanagan Valley consist of remnants from two major glaciations and two major non-glacial periods, as well as more recent sediments. The oldest sediments exposed in the Okanagan Basin are the Westwold Sediments that underlie the Okanagan Centre Drift deposits. The Westwold Sediments consist of gravely sand at the base and a relatively thinner unit of marl, sand, silt and clay at the top (Fulton and Smithe, 1978). The most significant amounts of Westwold sediments are found near Armstrong, Vernon, Lavington and Rutland (Nasmith, 1962). The Okanagan Centre Glaciation occurred approximately 43 800 years BP (Fulton and Smith, 1978), and drift sediments overlie the Westwold sediments. The Okanagan Centre Drift is characterized by an unstratified till, which is underlain by cobbly bouldery gravel and overlain by pebbly silt and gravel. Okanagan Centre Drift deposits occur at many localities throughout the basin. Nonglacial sediments, called Bessette Sediments, overlie the Okanagan Centre Drift and consist of silt, sand and gravel with some plant remains (Fulton and Smith, 1978). Bessette Sediments can be found near Lumby, on the east side of Lake Okanagan and in Rutland. Kamloops Lake Drift deposits overlie the Bessette Sediments, and can be correlated to the onset of the Fraser Glaciation at approximately 19 000 years BP. Kamloops Lake Drift consists of three units, with till as the middle unit. The lower unit comprises a thick (~23 meters), poorly-laminated silt and clay, and pebbly sand and bouldery gravel (Fulton and Smith, 1978). The upper unit underlies postglacial sediments or forms the present erosional surface, and includes well stratified silt, sand and gravel. The upper unit includes a thick succession of glaciolacustrine silt that is most visible in Penticton's famous silt bluffs.

The present morphology of the landscape is dominated by events that occurred during the late glacial stage, glacial retreat and recent processes. Lake Penticton formed during the late stages of the last glaciation, and extended from Okanagan Falls to

Enderby. Evidence for this massive lake is present along the valley sides. The most significant deposits that coincide with the present ground surface are located north and south of Armstrong, just east of Vernon, between Winfield and Kelowna, Westbank, and on both sides of Okanagan Lake from Summerland to Penticton (Nasmith, 1962). Kettled outwash deposits and outwash terraces are present along gully walls that enter the main basin. The outwash deposits are most prevalent along Osoyoos Lake, Oliver, Trout Creek, southeast Kelowna and the Spallumcheen Valley. River channels, stream-cut terraces, raised alluvial fans and deltas are features that formed by glacial meltwaters after ice had almost completely retreated from the valley (Nasmith, 1962). Raised alluvial fans and deltas are similar to current alluvial fans, except they were formed during a time when the base level was higher than the current level. The fans and deltas are present just above the base of many current tributaries that enter the valley, in Rutland and near Lavington. The late glacial river channels and stream-cut terraces are located around Oliver, and between Enderby and Swan Lake. Recent alluvial fans occur along the bottom of the valley and represent the product of modern tributaries. Most of the major towns (Armstrong, Vernon, Winfield, Kelowna, Summerland, Penticton and Oliver) are built on alluvial deposits. Okanagan River flood plain deposits run parallel to the current course of the Okanagan River. Minor amounts of beach, spit and dune deposits are present in Penticton and Lake Osoyoos.

2.2. SURFACE HYDROLOGY

The Okanagan Valley contains a chain of valley-bottom lakes that are connected by surface water channels as well as through the subsurface. The highest elevation lakes are located at the north end of the valley and east of the main basin that contains Okanagan Lake. In the sub-basin, water flows north from Ellison Lake to Woods Lake, and then to Kalamalka Lake. From Kalamalka Lake, water flows out of the sub-basin and into Vernon Creek where it turns south and drains into the Vernon arm of Okanagan Lake. The Okanagan River drains Okanagan Lake and flows south to Skaha Lake, Vaseux Lake and finally Osoyoos Lake. Okanagan Lake holds approximately 25 cubic kilometres of water, reaches a maximum depth of 230 meters, and easily forms the largest surface water feature in the valley (Ministry of Environment, 1981). The drainage of Okanagan Lake is controlled, and the lake levels are moderated to offset the effects of highly variable run-off in the valley. Okanagan Lake is subject to lose up to 1/3 of the annual run-off through evapotranspiration (Okanagan Basin Study, 1974). The valley lakes receive run-off through an estimated 130 tributaries and their associated headwater lakes; although, most tributary channels are dry from July to November. The elevation drops from 391 meters above sea level (masl) at Wood Lake to 278 masl at Osoyoos Lake; a total drop of 113 meters.

2.3. HYDROGEOLOGY

Aquifers in the Okanagan Valley are typically located along the bottom of the main valley or the bottom of sub-basins at higher elevations, except for the Myer's Flat aquifer, which is located within a hanging valley above Oliver. Usually, these aquifers are adjacent to the Okanagan River or a lake. The aquifers are either unconfined or confined, and consist of materials ranging from silty sand to gravel.

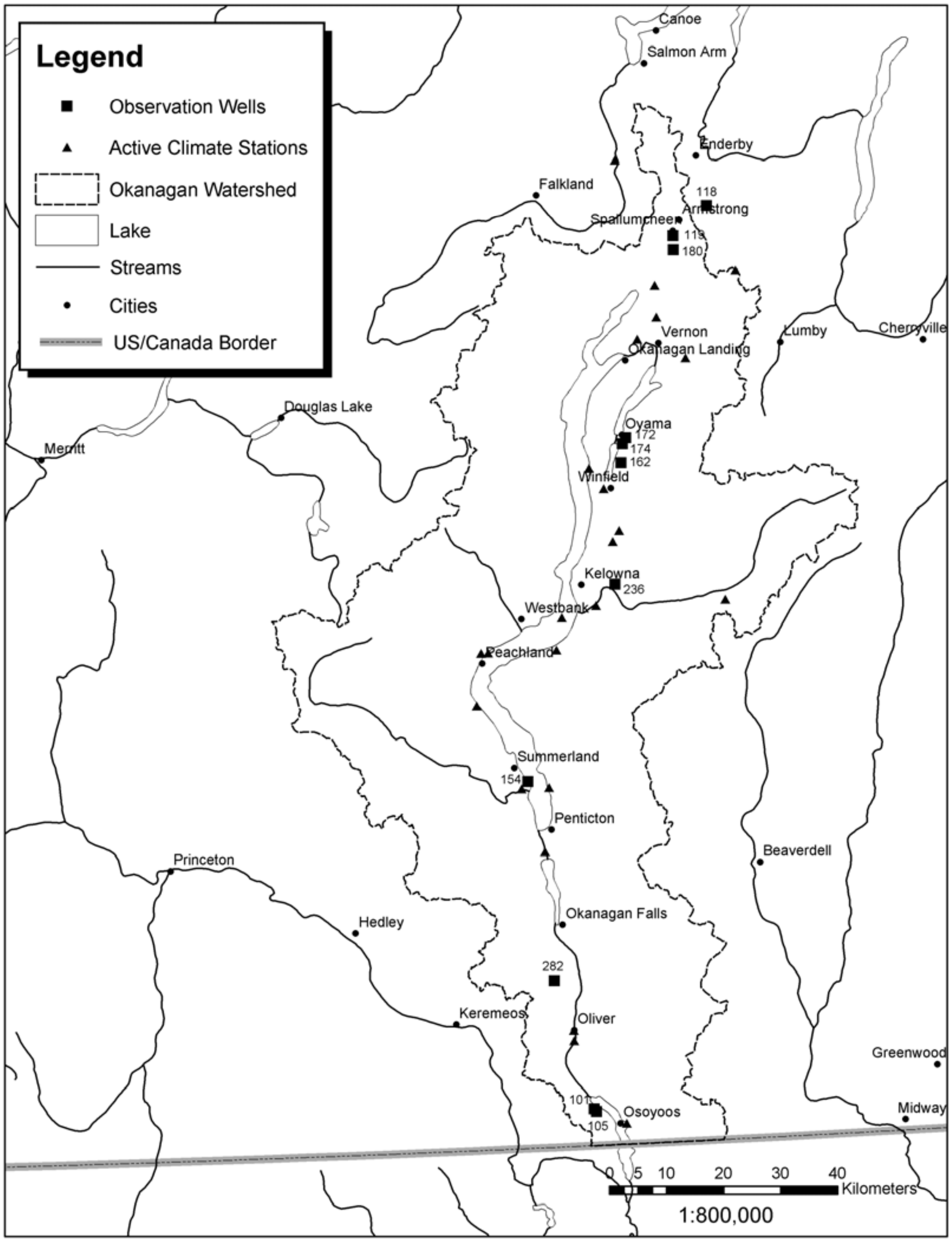
Every aquifer in BC is classified by the amount of development and the vulnerability of the aquifer according to the BCWLAP Aquifer Classification System (http://wlapwww.gov.bc.ca/wat/aquifers/reports/aquifer_maps.pdf). In general, unconfined aquifers that are highly permeable and heavily developed receive a greater vulnerability rating.

Regional groundwater flow is generalized as flowing from the north to the south, in the direction of surface water drainage. The north end of the basin may receive some groundwater flow from the Salmon River region as interbasin flow, but for the purposes of this study, Okanagan watershed is considered a self-contained groundwater basin. The watershed boundary (shown in Figure 2.1) roughly delineates the catchment area for groundwater recharge.

2.4. OBSERVATION WELL NETWORK

The Ministry of Water, Land and Air Protection maintains an observation well network in British Columbia. The network is used to monitor groundwater levels in unconfined and confined aquifers. A total of 33 active wells are located in the Okanagan Basin (Figure 2.1).

Figure 2.1 Observation wells and active climate stations in the Okanagan valley.



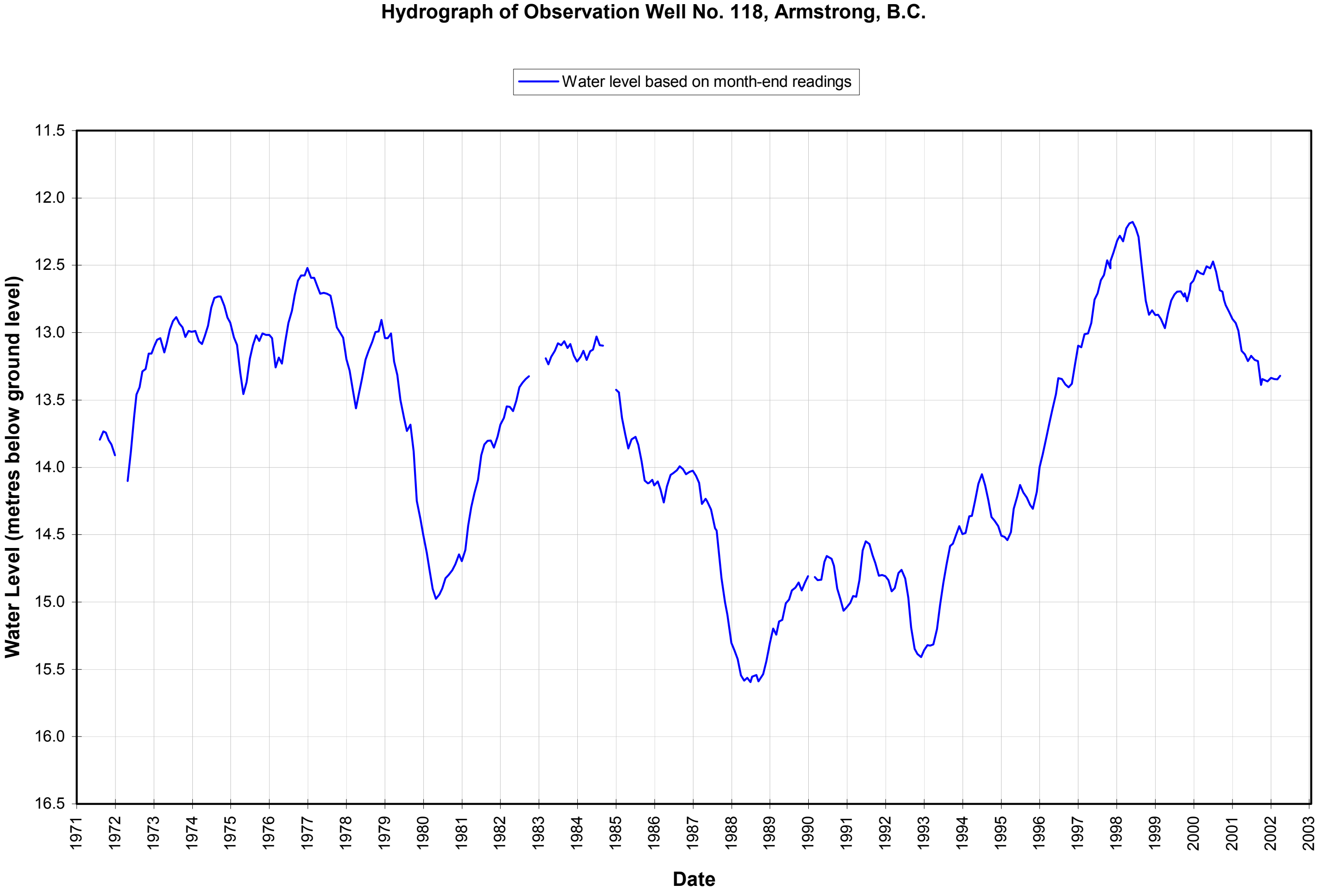
Water level data from the observation wells are gathered in two ways. Most six-inch diameter wells are equipped with a level logger that remains inside the well housing and records levels at daily to monthly intervals. The data are collected periodically and added to the Ministry's master data file. Most two-inch diameter wells do not have level loggers and are measured manually by a local observer on a monthly basis. Information on the physical dimensions of each well was extracted from the Ministry's WELL database.

A record of water level over time is displayed as a hydrograph (Figure 2.2). Hydrograph data were supplied by the BCWLAP (http://wlapwww.gov.bc.ca/wat/gws/obswell). A complete collection of well hydrographs is provided in Appendix A. Analysis of hydrographs can be done to determine direct groundwater recharge from precipitation. Chapter 5 describes the methodology used in this study for estimating recharge from observation well hydrographs.

2.5. CLIMATE DATA

Historic records of climate data are available from a network of climate stations situated throughout Okanagan Basin (Figure 2.1). Environment Canada supplied raw data, climate normals and map files for use in this project. Climate normals require a continuous 30 year period of measurements. Some of the climate stations have 30 years of continuous data, giving a reasonable representation of climate for the areas represented, while the climate for other areas were compiled from inactive and active stations in the area, each with shorter periods of record (POR). Each climate station records a variety of information, but for this study, the main parameters used were precipitation and temperature.

Figure 2.2 Hydrograph showing the fluctuation of water levels in observation well 118 located in Armstrong, BC.



3. SLUG TESTING AND ANALYSIS

3.1. WHAT IS A SLUG TEST?

Slug testing is a method of estimating physical properties of an aquifer using a well. Typically, a slug test involves the insertion of a solid cylinder of known volume that causes an abrupt change in the water level. A record of the head level as it returns to the initial undisturbed (static) water level, also called recovery data, is used to calculate the hydraulic conductivity (K) of the aquifer. A slug insertion test is called a falling head test, or slug-in test. An equally valid type of test involves slug extraction, also called a rising head test, or slug-out test.

The product of a successful slug test is a record of the water level decay after slug insertion, or extraction (Figure 3.1 and 3.2). A recovery record comprises measurements at an interval appropriate to the duration of the test, and detailed enough to show rapid water level changes at the beginning of the test. A logarithmic measurement interval is ideal for slug testing where the interval between measurements is short in the beginning and longer near the end of the test. The water level changes are usually too quick to be measured by hand using a water level tape, although it may be possible in low conductivity material. The most accurate way to obtain water level measurements is to use a pressure transducer with datalogger placed below the end of a fully submerged slug.

Figure 3.1 A typical water level response to a slug insertion, or slug-in, test. The graphical output was produced by the datalogger (TROLL 4000) software and is a representation of the pressure readings at the level of the inlets on the pressure transducer. The abrupt change in water level is difficult to resolve at the beginning of the test, but water level decay is characteristic of a slug-in test.

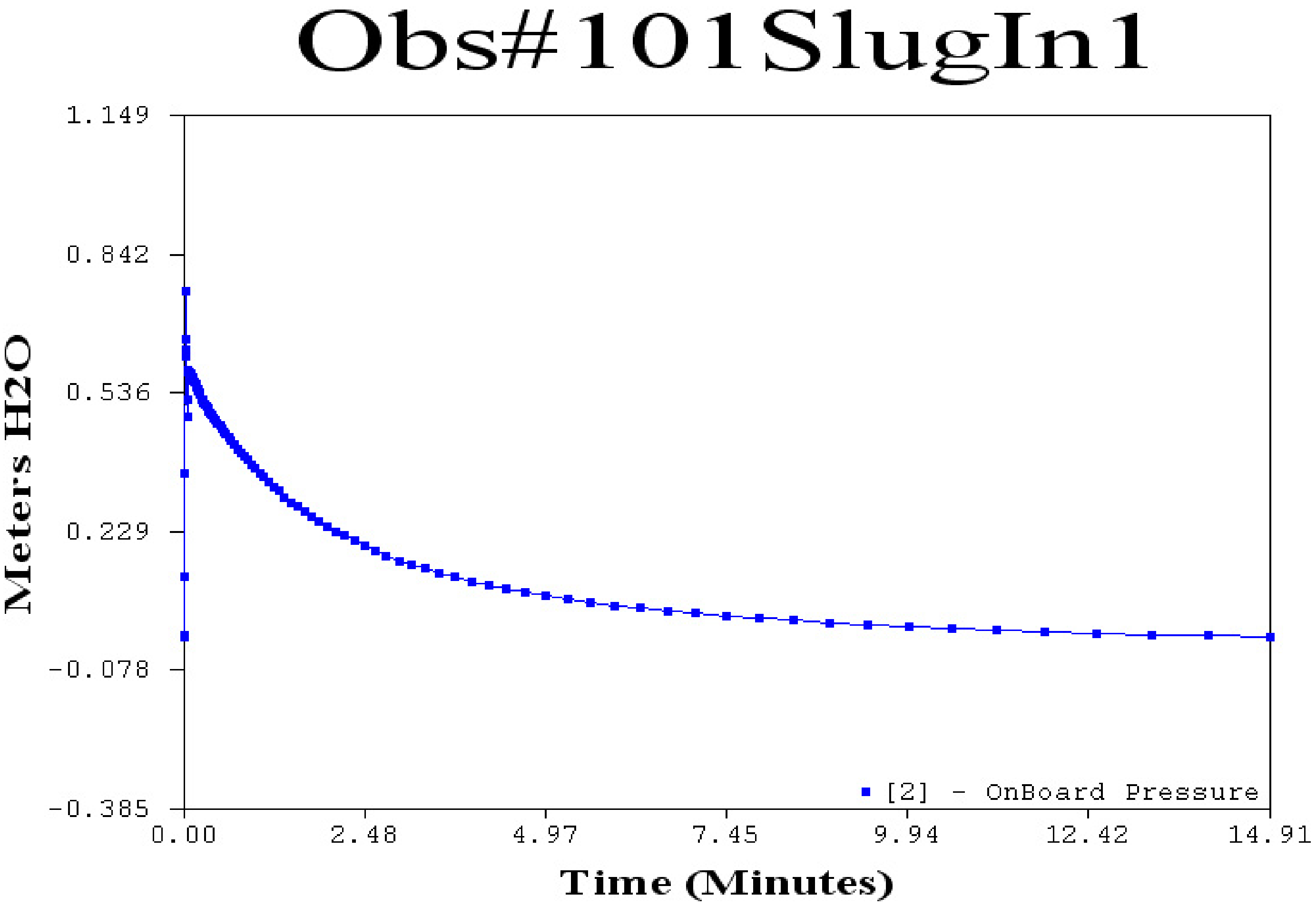
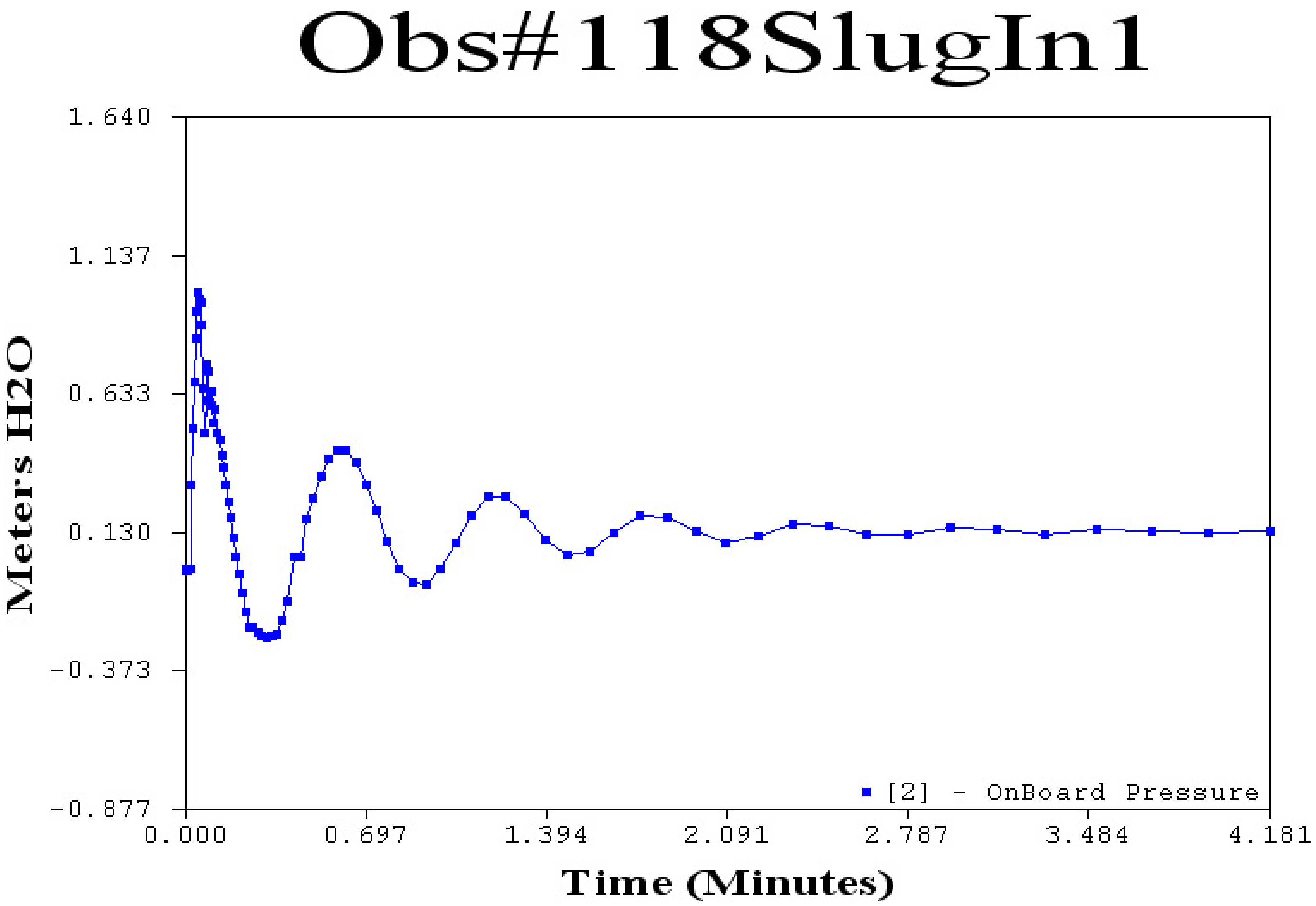


Figure 3.2 A non-typical, under-dampened response to a slug insertion. The inertial effects of rapid slug insertion are not dampened by the formation (or the well screen), and the water level oscillates like ripples in a pond.



3.2. WELL SELECTION

Of the 33 observation wells in the Okanagan, 13 wells were determined to be suitable for slug testing for the following reasons:

1. some wells were not available because land ownership had changed and access to the wells remained in question;
2. some wells were in active use by municipal water suppliers;
3. some wells had been damaged by vandalism;
4. the well diameters for some wells were too large to induce a significant response with a hand-operated slug;
5. at the time of testing, the water level was too low to permit a slug test;
6. redundancy of information and time constraints of the field session (e.g., some wells in Summerland and Osoyoos were not used).

Table 3.1 lists the observation wells used in the slug testing program and describes the location, physical characteristics and general geology of the aquifer. Physical parameters of the wells were determined from the BCWLAP well log data base and portable document files scanned from original well reports (Appendix A). A table outlining the candidate wells in the Okanagan is also included in Appendix B. Unfortunately, observation well #332 showed no response during slug testing. The well screen may have been clogged, corroded or collapsed, and a rusty film of water was left on the slug after it was raised.

Table 3.1 Observation wells located in the Okanagan Valley.

Observation Well No.	**Location**	**Diameter**		**Depth TOC**		**Screen Top**		**Screen Bottom**		**Screen Length**		**Static Water Level**		**Un\Confined Aquifer**	**Aquifer Description**
		in.	**m**	**feet**	**m**	**feet**	**m**	**feet**	**m**	**feet**	**m**	**feet**	**m**		
96	Osoyoos	2	0.051	35	10.60	28	8.534	33	10.058	5	1.524	14.55	4.435	unconfined	silty clay
101	Osoyoos	2	0.051	64	17.79	57	17.374	62	18.898	5	1.524	12.33	3.758	unconfined	sandy silt & gravel
105	Osoyoos	2	0.051	42.5	12.20	35.5	10.820	40.5	12.344	5	1.524	9.37	2.855	unconfined	silty clay & gravel
118	Armstrong	7	0.178	1570	478.50	1016	309.677	1026	312.725	10	3.048	48.88	14.898	confined	sand & gravel
119	Armstrong	7	0.178	590	179.83	270	82.296	280	85.344	10	3.048	110.04	33.540	confined	coarse sand
154	Summerland	2	0.051	49	12.60	38	11.582	43	13.106	5	1.524	14.86	4.530	confined	silty sand & clay
162	Oyama	6	0.152	13.5	5.10	9	2.743	13	3.962	4	1.2192	10.73	3.270	unconfined	shale bedrock
172	Oyama	6	0.152	66	20.12	61	18.593	66	20.117	5	1.524	56.77	17.303	unconfined	gravel
174	Oyama	6	0.152	135	41.15	129	39.319	133	40.538	4	1.2192	120.73	36.798	unconfined	pebbly gravel
180	Armstrong	6	0.152	123	37.49	113	34.442	123	37.490	10	3.048	42.58	12.978	unconfined	fine-med sand
236	Rutland	6	0.152	140	42.67	131	39.929	140	42.672	9	2.7432	81.41	24.815	confined	sand & gravel
282	Myer's Flat	6	0.152	55	16.76	46	14.021	55	16.764	9	2.7432	44.95	13.700	unconfined	sand & gravel
332	Oliver	6	0.152	120	36.50	77	23.470	91	27.737	14	4.2672	60.79	18.530	unconfined	fine-med sand
356	Winfield	6	0.152	40	12.20	36	10.973	40	12.192	4	1.2192	28.51	8.689	unconfined	silty sand & gravel

*Note TOC = Top of casing

3.3. SLUG DESIGN

BCWLAP has fitted most 6-inch diameter wells with a protective housing (Figure 3.3). The protective housing is approximately 55 cm high, and restricts the insertion of a longer slug. To initiate a significant response within the well, a slug longer than 55 cm was required. Therefore, a slug was specially designed for these wells. The slug was constructed from high-density PVC plastic, cut into 15-inch sections that could be assembled at the top of the well (Figure 3.4). Two particular sections of the slug assembly were unique: the nose cone and tail piece. The nose cone is slightly tapered to reduce slapping and splashing upon entry. The tail piece has an eye ring on the end to attach the rope. Half-inch holes were drilled perpendicular to the length of the slug and within a couple inches of the back of each section. A brass assembly pin could be inserted during assembly, so the assembled part of the slug could dangle in the well while the remaining sections were screwed on. The five 15-inch sections created a total slug of 75 inches that was 3 inches in diameter. A solid 45-inch section is also available to speed up the slug testing procedure at well with no protective housing.

A data cable attaches the pressure transducer to a lap top computer at the surface, and allows the user to retrieve recovery data as the slug test proceeds. In this particular study, a Troll 4000 datalogger was employed. Win-Situ is specialized software (In-situ Inc., 2000) used to retrieve, store and display data.

Figure 3.3 An observation well with a protective housing at the top of the casing. A slug test was in progress at the time the photograph was taken.

Figure 3.4 Slug testing apparatus used in the Okanagan Basin. (1) 1.25” diameter slug used in 2” wells; (2) 45” long section of 3” diameter slug assembly used in 6” or larger wells; (3) 15” long sections of 3” slug assembly; (4) TROLL 4000 data logger / pressure transducer; (5) 40m data cable; (6) nylon rope; (7) assembly pins.

3.4. FIELD TESTING METHODS

The slug testing methodology used in the field was adapted from the procedures outlined in *The Design, Performance and Analysis of Slug Testing* (Butler, 1998). The slug testing program was designed to produce a reliable estimate of hydraulic conductivity, K, for the aquifer immediately surrounding the well, and to develop a rigorous procedure to be followed at each test well.

Most wells in the observation network were constructed for monitoring purposes, so well development was often neglected or was undertaken to a minimal degree. Slug testing produces a small disturbance in the water table and the response is constrained to a small distance from the well casing. Well development activities remove fine debris from around the well screen. Where little development has occurred, plenty of fine material may remain around the well screen, and the response of the slug test can be directly affected by the level of development at the well. In order to determine if a low-permeability well skin had formed during the test[1], three or more slug tests were performed at each well. Both insertion (slug-in) and extraction (slug-out) were used as a way of repeat testing each well to identify well skin effects.

The values of hydraulic conductivity obtained for the aquifer should be independent of the level of forcing during the test. Different initial head displacements can show that well response is not dependent on the size of the slug. Falling head (slug-in) and rising head (slug-out) tests are valid ways of using different initial head displacements, as well as varying the size of the slug.

In all tests, the slug should be inserted and withdrawn in a near instantaneous fashion relative to the response of the well. To determine if the slug was inserted instantaneously, the level of the observed head change caused by the slug should roughly match the expected head change calculated from the volume of the slug.

A slug test conducted in a highly conductive formation will respond rapidly. In a gravel or course sand aquifer, the slug test will last less then a minute. A pressure transducer,

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[1] Well skins are produced by the migration of fine particulate matter into the well screen. Skins are more commonly found in poorly developed wells.

capable recording 3 or 4 readings per second, is required to produce a good recovery curve. A logarithmic time interval is ideal for gathering water level data, as the initial response to slug insertion is rapid and slowly decays as the test proceeds. Thus, a logarithmic measuring interval began with 4 measurements per second and the time between measurements increased logarithmically.

Slug testing was performed between July 26 and July 30, 2004. Before a slug test could be conducted at an observation well, the Thalimedes data logger had to be removed. Des Anderson (BCWLAP) and Trina Koch (BCWLAP) assisted in preparing the well for testing by properly removing the data recorder. The data stored within the recorder were downloaded and the water level in the well was measured so the instrumentation could be re-inserted and recalibrated after the test was complete. With an open well and accurate measurement of water depth, the distance that the slug had to be lowered could be determined. The slug must fully submerge during insertion, so the length of rope required was equal to the depth of the water. The distance was marked with red tape along the rope. To achieve an instantaneous insertion, the nose of the slug should be as close to the water surface level before commencement. As a guide, a piece of green tape was placed along the rope that was exactly the length of the slug shorter than the red mark. The proximity of the slug to the water surface was determined by a short pull on the rope, and the resulting small splash of the slug on the water surface.

When the slug was in place, the operator would signal to the assistant to start the data logger. It is important to initiate insertion with the beginning of recording so the fine-scale measurements will occur during the most rapid response. Once the slug was fully inserted, great care was taken to not disturb the rope. The progress of the test was monitored through the laptop computer, and the test was concluded when the water level returned to the initial level. With the slug fully inserted, and the water at static level, an extraction test could be immediately performed. The sectional design of the slug made changing the volume of the slug as easy as adding or removing sections of the slug. All original slug test data is included in Appendix B as text documents (.txt) and Win-Situ files (BIN files).

3.5. SLUG TEST ANALYSIS

Most of the wells tested were completed in unconfined aquifers screened below the water table, and a few of the wells were completed in confined aquifers screened below the water table. The analysis was carried out according to recommendations made by Bulter (1998). The Bouwer and Rice (1976) method is a suitable procedure for analyzing the recovery data from slug tests conducted in unconfined aquifers. The Horslev (1951) and Cooper-Bredehoeft-Papadopulos (1967) methods were applied to recovery data from the confined aquifers in partially penetrating wells. The oscillatory response exhibited by observation well #118 was experimentally analyzed using an automated curve matching program (Aqtesolv, 2003) that is referred to as the *Butler* method.

It is common for all head level measurements to be first converted into normalized head data with the following equation:

$$\text{Normalized Head} = \frac{H(t)}{H_o} \qquad [3.1]$$

where:

$H(t)$ = water level height at time, t (m);

H_o = initial water level displacement (m).

There were three main types of responses observed in the normalized recovery data plotted on a semi-logarithmic plot. The first type of response showed an initial displacement that linearly decayed back to the static water level (Figure 3.5). Linear decay of the water level is a typical response that is expected under ideal conditions where no water is removed from storage as the test progresses. The second type of response showed a decay curve that was concave-upward as it returned to static water level (Figure 3.6). A concave-upward shape indicates that water is affected by the

Figure 3.5 Logarithm of normalized head vs. time plot shows linear decay in observation well #119, Armstrong, BC.

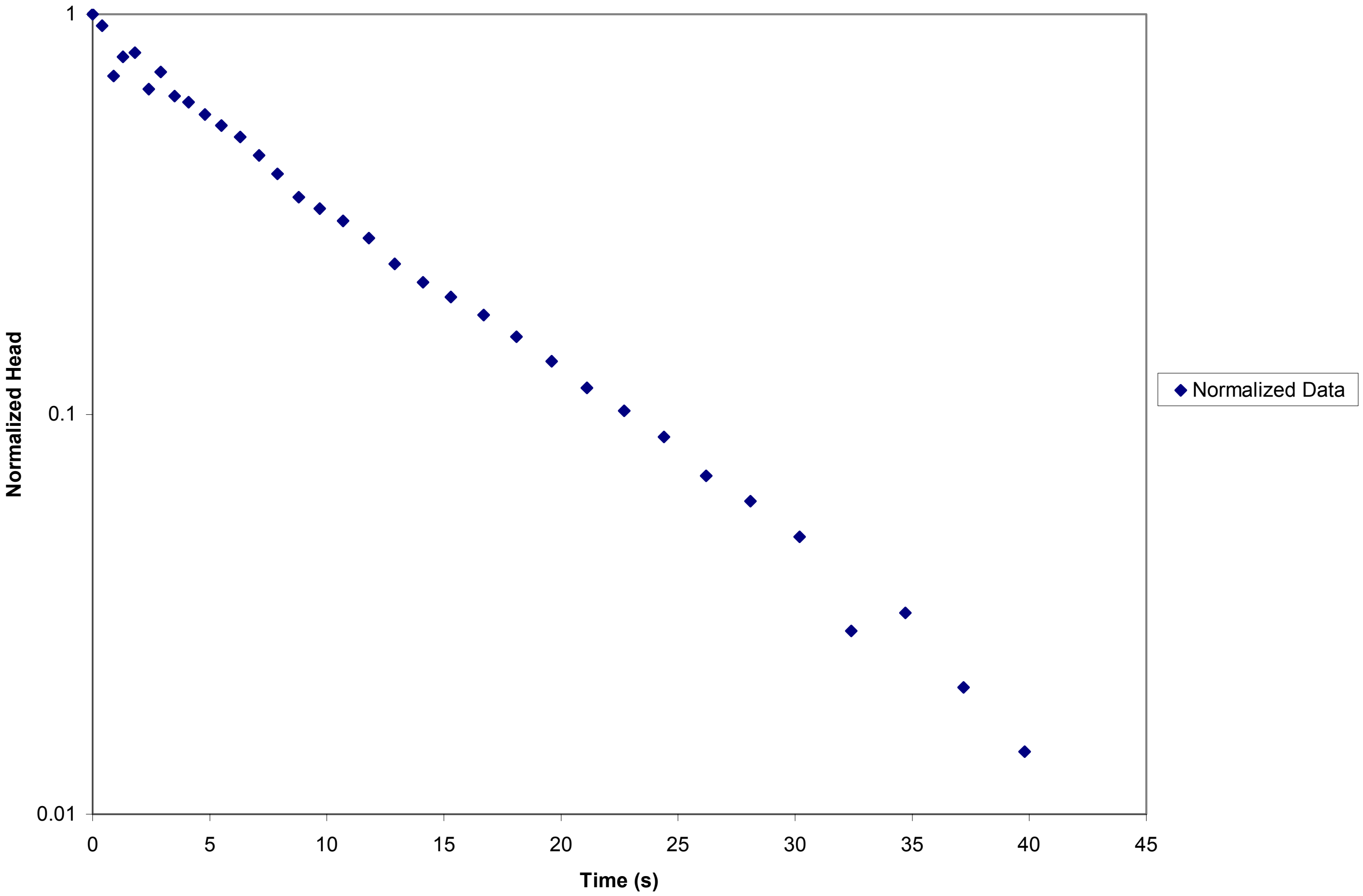


Figure 3.6 Logarithm of normalized head vs. time plot shows influence of storage parameter in observation well #356, Winfield, BC.

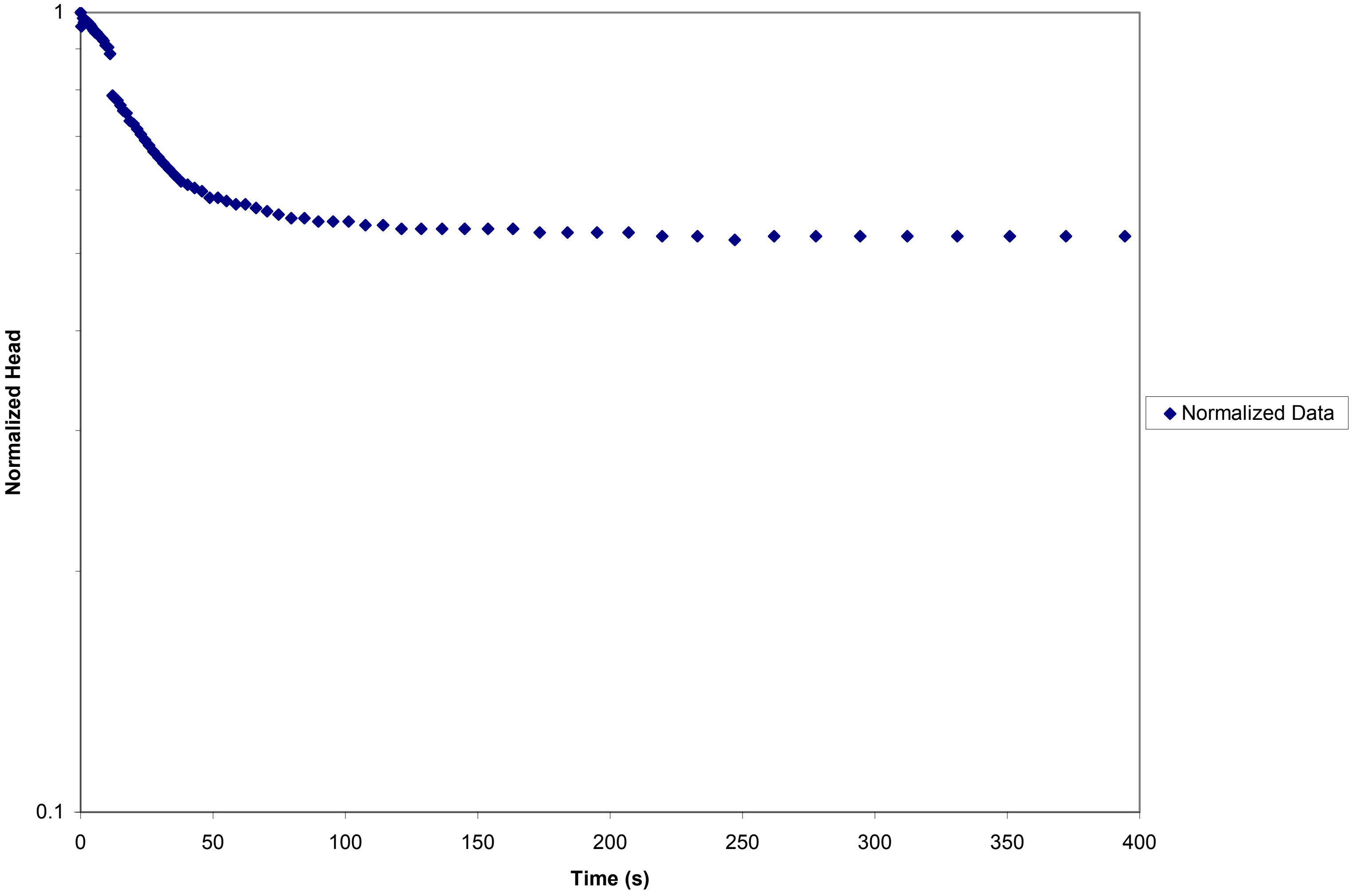
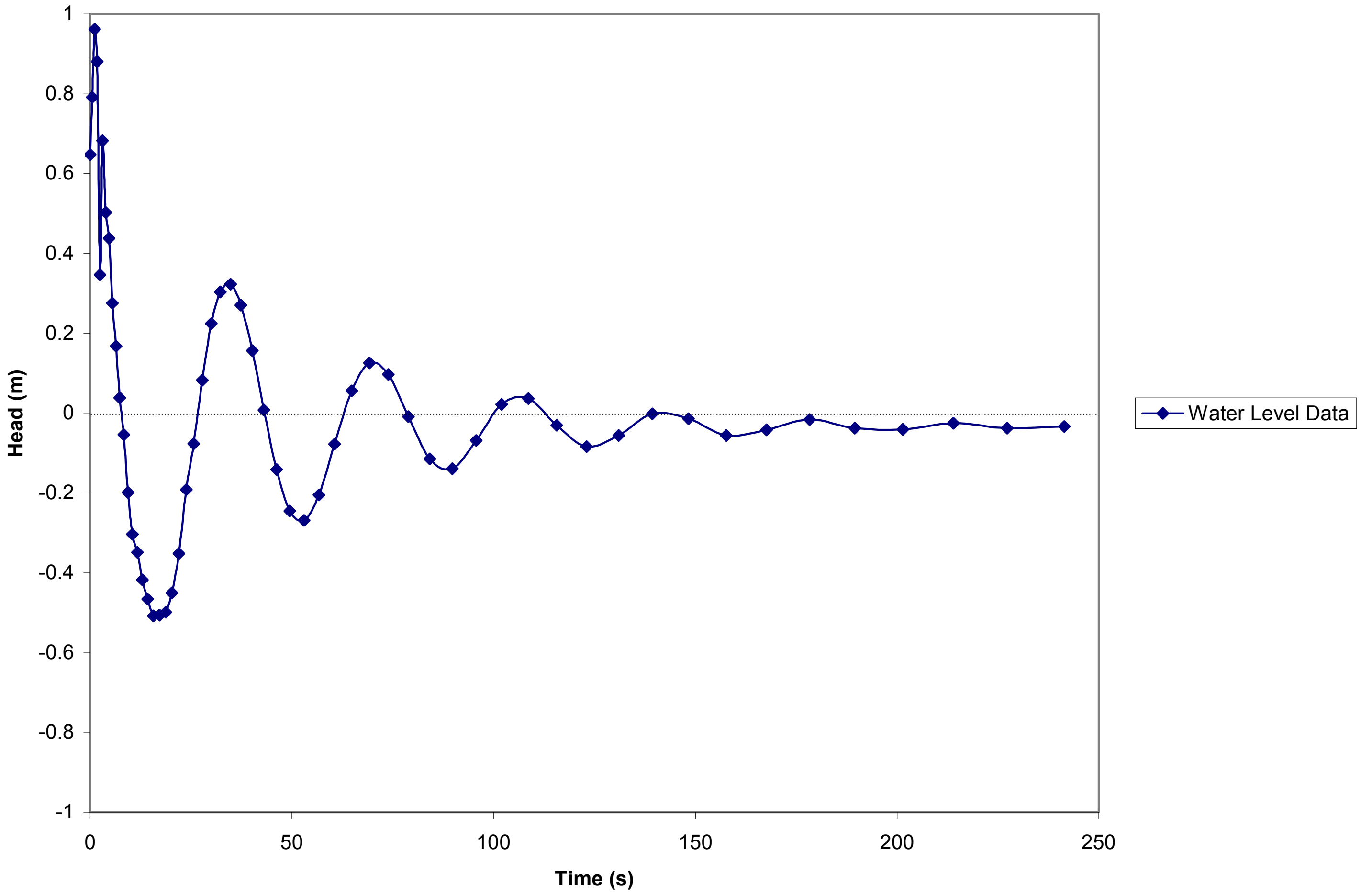


Figure 3.7 Normalized head vs. time plot shows oscillatory response in observation well #118, Armstrong, BC.



storage parameter of the aquifer. The third type of response showed oscillatory fluctuations as the water level returned to static (Figure 3.7). An oscillatory response indicates that the primary controlling mechanism is the inertia of the water column (Butler, 1998). In an under-damped response, more water flows into or out of the well than predicted by conventional models.

3.5.1. BOUWER AND RICE METHOD

The Bouwer and Rice method is applicable to unconfined aquifers screened below the water table and the majority of wells tested in the Okanagan. The Bouwer and Rice method is based on a mathematical model and two key assumptions: (1) the effects of elastic storage are negligible, and (2) the position of the water table does not change during the course of the test. The formula used for determining the radial component of hydraulic conductivity can be written as follows (Bouwer and Rice, 1976):

$$K_r = \frac{r_c \ln\left[R_e / r_w\right]}{2T_o} \qquad [3.2]$$

where:

K_r = radial component of hydraulic conductivity (m/s);

r_c = effective radius of the well casing (m);

R_e = effective radius of slug test (m);

r_w = effective radius of well screen (m);

T_o = lag time (s), time at which normalized head is 0.368.

The value of the effective radius of the slug test, Re, is not the actual effective radius of the slug test, but rather an empirical parameter that is determined using the following expression:

$$\ln\left(R_e / r_w\right) = \left[\frac{1.1}{\ln\left(\left(d+b\right)/r_w\right)} + \frac{A + B\left(\ln\left[\left(B - \left(d+b\right)\right)/r_w\right]\right)}{b/r_w}\right]^{-1} \qquad [3.3]$$

where:

d = depth of the well (m);

b = length of the screen (m).

$$A = 1.4720 + 3.537 \times 10^{-2}(b/r_w) - 8.148 \times 10^{-5}(b/r_w)^2 + 1.028 \times 10^{-7}(b/r_w)^3 - 6.484 \times 10^{-11}(b/r_w)^4 + 1.573 \times 10^{-14}(b/r_w)^5 \quad [3.4]$$

$$B = 0.2372 + 5.151 \times 10^{-3}(b/r_w) - 2.682 \times 10^{-6}(b/r_w)^2 - 3.491 \times 10^{-10}(b/r_w)^3 + 4.738 \times 10^{-13}(b/r_w)^4 \quad [3.5]$$

The original mathematical equations produced by Bouwer and Rice incorporated an anisotropy ration, r_w^*:

$$r_w^* = r_w (K_z / K_r)^{1/2} \quad [3.6]$$

where:
K_z = vertical hydraulic conductivity (m/s).

Since no previous information on the anisotropy of the aquifer was available at the time of analysis, r_w^* was assumed to be 1.

To analyze recovery data with the Bouwer and Rice method, the short-period interference caused by the introduction of the slug was removed (Pandit and Miner, 1986). The point on the graph that showed stable head measurements was taken to be the start of the test, and the graph was effectively translated to coordinate with the beginning of the test (Figure 3.8). The next step was to plot the logarithm of the normalized head values against the time since the test began. At this point, a straight line was fit to the curve through visual inspection or an automated regression method (Figure 3.9). Butler (1996) recommends that the straight line be fit to normalized heads in the range of 0.20 to 0.30, especially when the plot shows a non-linear trend. The slope of the fitted line is then used to calculate T_o. The slope is equal to the value of $-1/T_o$ when written in terms of the natural logarithm.

The observation well used as an example in Figure 3.9 shows two distinct portions of the test (Figure 3.10). Observation well #96 was installed with a gravel pack of unknown radius. The first, more steeply sloping, section of the plot is assumed to represent the

Figure 3.8 A head vs. time plot of a slug test in observation well #119 at Armstrong, BC. The initial displacement caused by the slug introduction is not instantaneous relative to the formation response, and early-time noise is generated at the beginning of the test. The initial head displacement (H_o) and the time of test initiation (t_o) are translated to avoid early-time noise. Analysis is conducted as if the test initiated at point P.

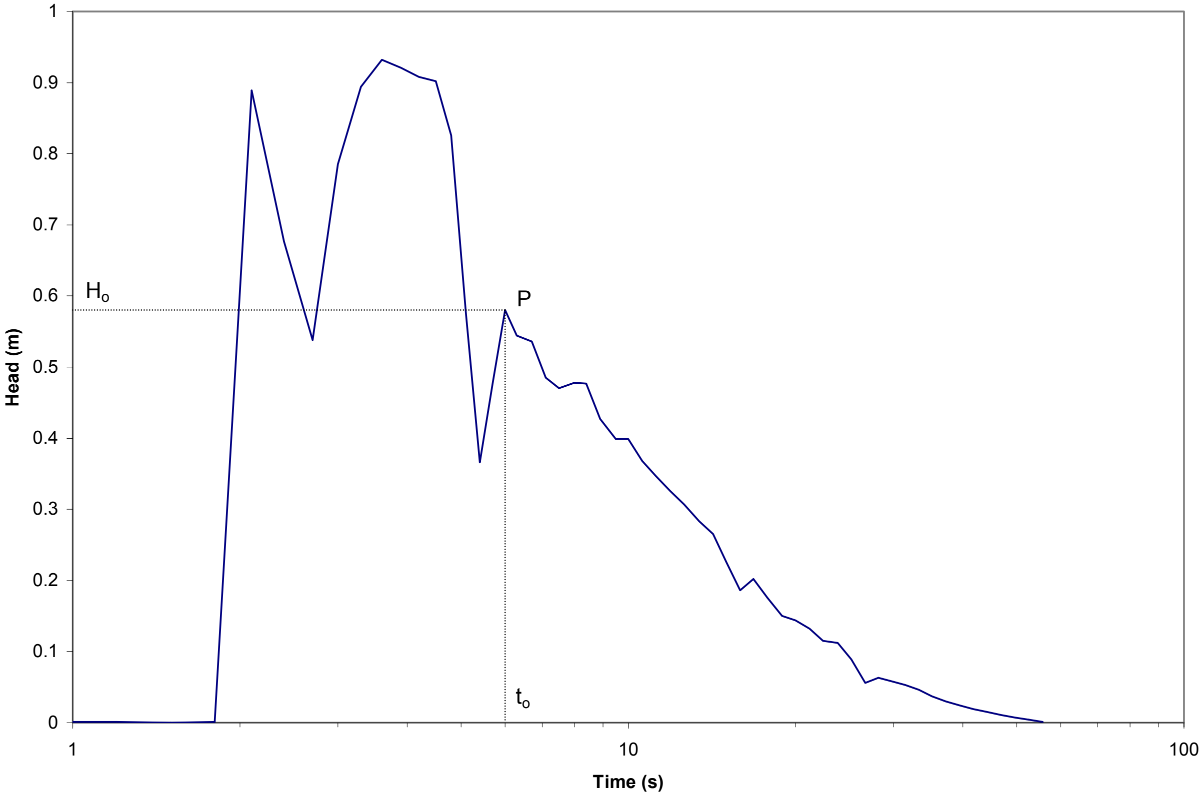


Figure 3.9 An example of the Bouwer and Rice method applied to recovery data from observation well #96 in Osoyoos, BC. A straight line is fit to the portion of the plot where normalized head values are between 0.20 and 0.30. The equation of the line in terms of the natural logarithm is $\ln(y) = -0.0143x + 0.017$. The corresponding lag time (T_o) is 69.9 seconds.

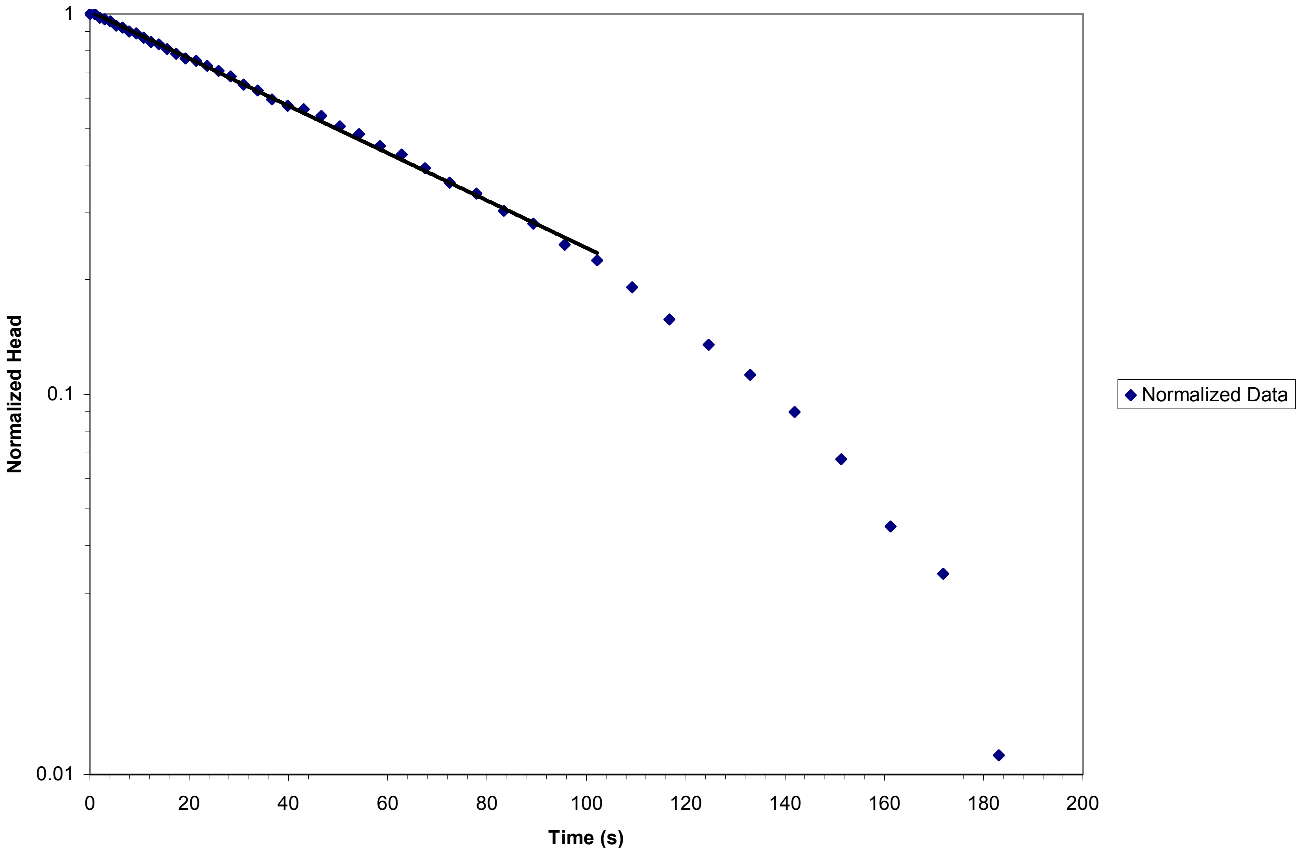
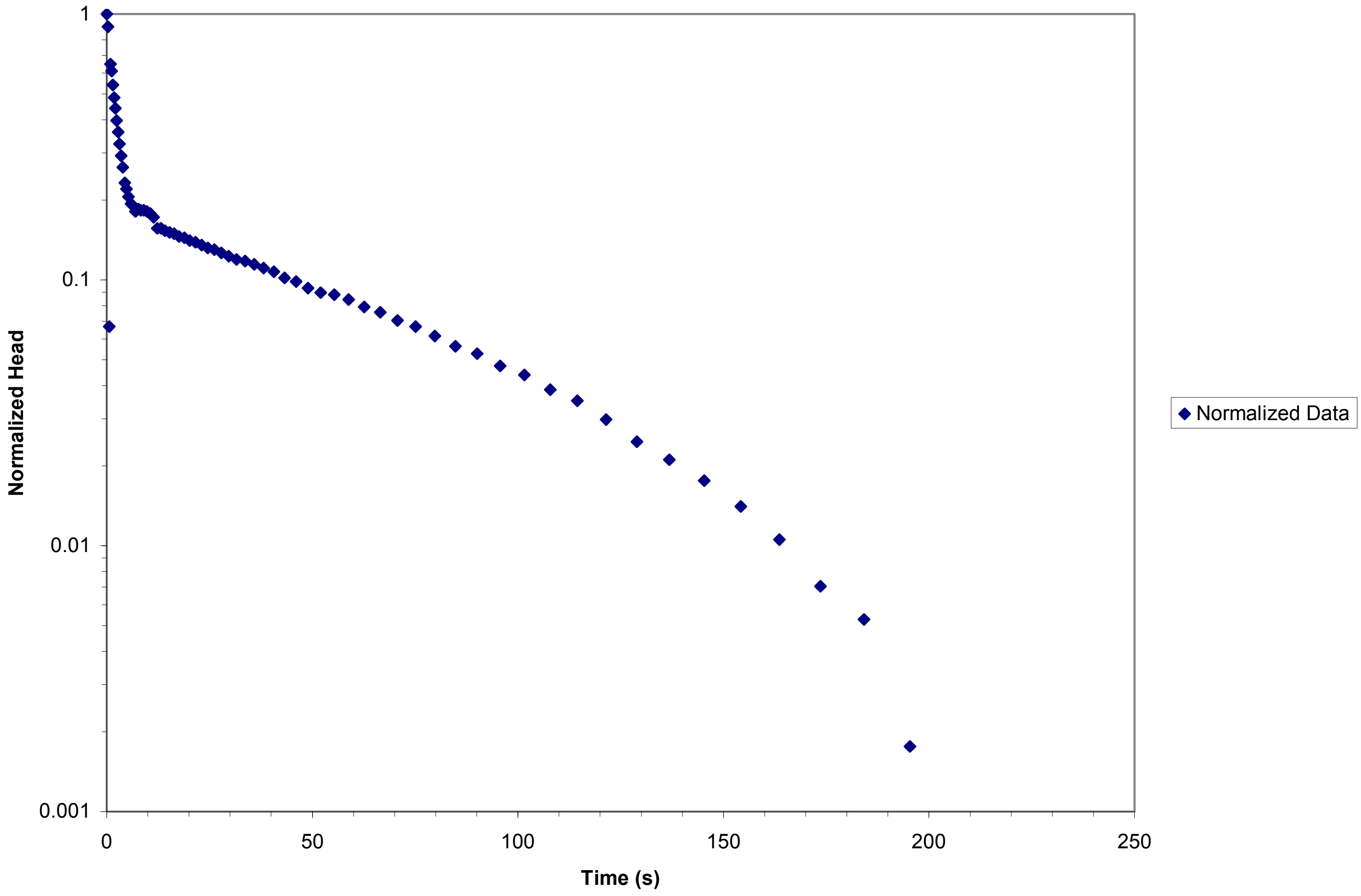


Figure 3.10 A logarithm of the normalized head values vs. time plot of a slug test in observation well #96 at Osoyoos, BC.



gravel pack, and the second section is assumed to represent the aquifer. The line was fit to the second section of the plot to determine the hydraulic conductivity of the formation rather than that of the gravel pack.

3.5.2. HVORSLEV METHOD

The Hvorslev method is applicable to confined aquifers screened below the water table, and is a popular method of analysing slug test recovery data. The Hvorslev method is based on a mathematical model (Hvorslev, 1951) and can be written as follows (Chirlin, 1989):

$$\ln\left(\frac{H(t)}{H_o}\right) = -\frac{2K_rBt}{r_c^2\ln(R_e/r_w)} \qquad [3.7]$$

where:

H(t) = head level above static at time, t (m);
H_o = initial head displacement (m);
K_r = radial component of hydraulic conductivity (m/s);
B = formation thickness (m);
r_c = effective radius of well casing (m);
R_e = effective radius of the slug test (m);
r_w = effective radius of well screen (m).

Two important assumptions are made in this formula: (1) the specific storage value is so small that its effects are negligible, (2) the constant head boundaries are a finite distance (R_e) distance from the test well. The effective radius of the slug test, R_e, is an empirical parameter that can be estimated by substituting either the length of the well screen, or a distance 200 times the radius of the well screen (U.S. Department of Navy, 1961).

The first step in the method involves plotting the logarithm of the normalized response data versus the time since the test began. If early time noise exists in the response data, the beginning of the test may be translated to a part of the curve where stable head values begin (as described above). A straight line is then fit to the data visually or through an automated regression method (Figure 3.11). In some situations, the storage mechanism will have an affect on the recovery data, and the plot will display a distinct concave-upward shape. Butler (1996) recommends fitting the straight line to normalized head data in the range of 0.15 to 0.25. The slope of the fitted line can be calculated and substituted into the equation:

$$K_r = \frac{r_c \ln\left(R_e / r_w\right)}{2BT_o} \qquad [3.8]$$

where:

T_o = lag time, time at which the normalized head is 0.368.

The value of $-1/T_o$ is equal to the slope of the line when expressed in terms of the natural logarithm. Equation 3.8 is used to determine the radial component of the hydraulic conductivity. The lag time (T_o) corresponds to the time when the normalized head is approximately equal to a normalized head value of 0.368.

All of the wells in the study area are partially penetrating wells. The Hvorslev analysis changes slightly for partially penetrating wells:

$$K_r = \frac{r_c^2 \ln\left[1/(2\Psi) + \left(1 + \left(1/(2\Psi)\right)^2\right)^{1/2} \right]}{2bT_o} \qquad [3.9]$$

where:

$$\Psi = \frac{\left(K_z / K_r\right)^{1/2}}{\left(b / r_w\right)} = \frac{\sqrt{\text{anisotropy ratio}}}{\text{aspect ratio}} \qquad [3.10]$$

b = screen length (m).

In all cases, no previous information on the radial and vertical hydraulic conductivities was known, and the anisotropy ratio was assumed to be 1.

3.5.3. COOPER-BREDEHOEFT-PAPADOPULOS METHOD

The Cooper et al. (1976) method is suitable for use in a partially or fully penetrating well in a confined aquifer. When the method is applied to partially penetrating wells, the formation thickness, B, is replaced by the effective screen length, b. The Cooper et al. method is based on a mathematical model, and makes some assumptions about the testing conditions: (1) the formation is homogeneous and exhibits Darcian flow, (2) the slug is introduce instantaneously, (3) hydrogeologic boundaries are at a great distance from the well, and (4) the elastic storage mechanisms (S_s) affect test responses.

The analytical solution to the mathematical model is:

$$\frac{H(t)}{H_o} = f(\beta, \alpha) \qquad [3.11]$$

where:

$\beta = \frac{K_r B t}{r_c^2}$, the dimensionless time parameter; [3.12]

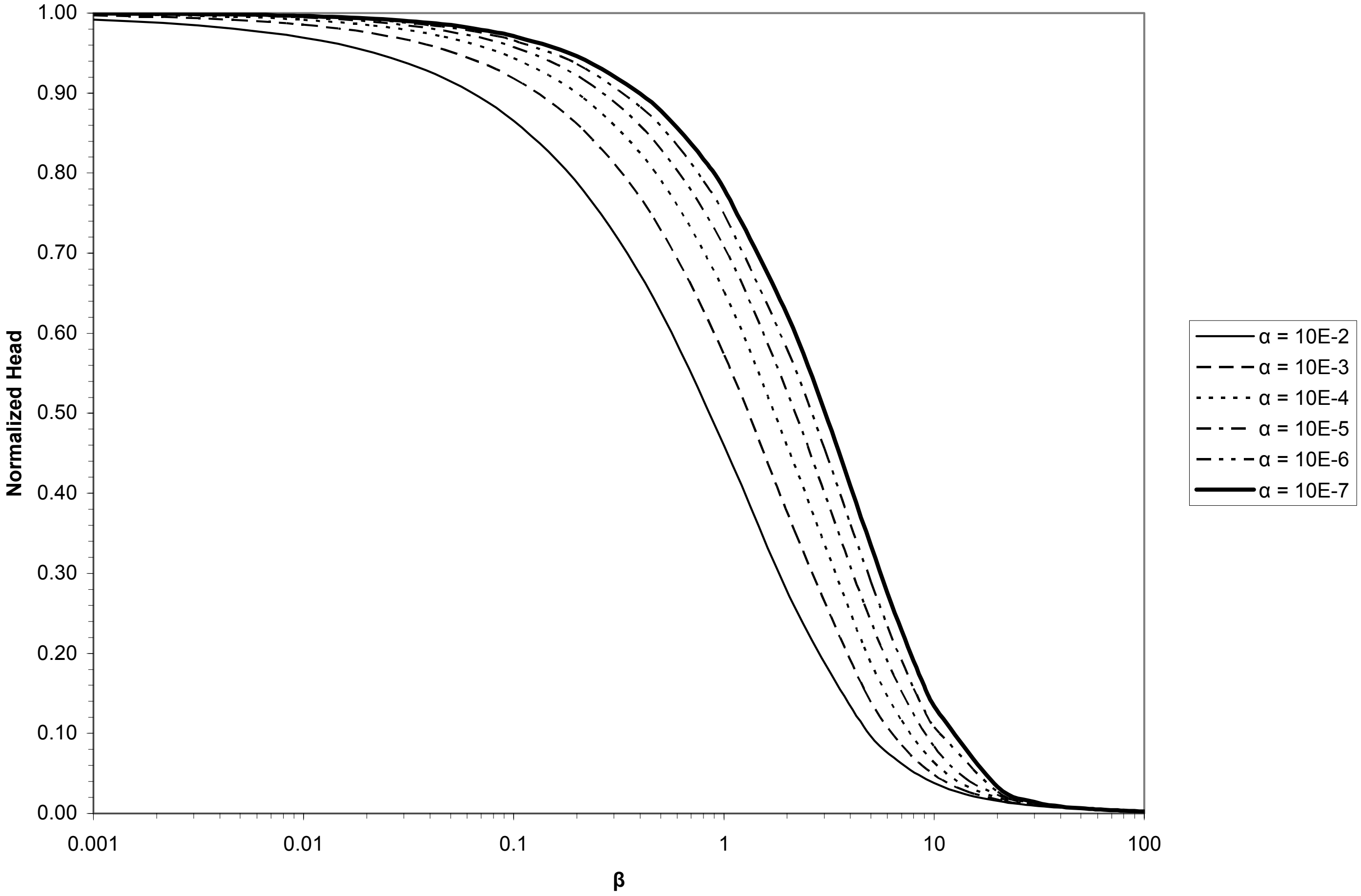
$\alpha = \frac{(r_w^2 S_s B)}{r_c^2}$, the dimensionless storage parameter; [3.13]

S_s = specific storage (m^{-1}).

The solution to Equation 3.11, when plotted as normalized head versus the logarithm of β, is a series of curves that correspond to different values of α (Figure 3.11). The method involves fitting one of the type curves to normalized recovery data plotted against time since the test began. The data plot is prepared with the same scale and number of log cycles. The type curves are moved parallel to the x-axis of the data plot until the curves are approximately matched. For convenience, β is set to 1.0 and the actual time since to the test began ($t_{1.0}$) is read off the data plot. The value of α is determined from the curve that most closely matches the data plot, and hydraulic conductivity is calculated from the formula for β (β=1.0):

$$K_r = \frac{r_c^2}{b t_{1.0}} \qquad [3.13]$$

Figure 3.11 Normalized head vs. the logarithm of β, type curves for the Cooper et al. method (from Abbey, 2000).



The specific storage can be calculated from the definition of α:

$$S_s = \frac{\alpha r_c^2}{r_w^2 b} \qquad [3.14]$$

Although, specific storage estimates can be obtained using the Cooper et al. method, Butler (1998) warns that uncertainty becomes large as the value of α becomes small.

3.6. RESULTS

The bulk of the analysis was completed using an automated curve matching program, AquiferTest version 3.0 (Waterloo Hydrogeologic Inc., 2004), and outputs are included in Appendix B. Manual calculations were performed to verify that the results were a good approximation of hydraulic conductivity. The hydraulic conductivity values for each observation well are summarized in Table 3.2. The under-damped response shown in observation well #118 was not analyzed by methods suggested by Butler (1998). The complexity of the analysis and quantity of wells showing this type of response seems to be beyond the scope of this work; however, the recovery data for observation well #118 were entered into Aqtesolv (2002) and the results included in Table 3.2. Note that the actual graphs created in Aqtesolv could not be saved (demo version of software used), and these do not appear in the Appendix.

The values shown in Table 3.2 approximately correspond to the expected conductivity values for the aquifer composition. Tables 3.3 and Table 3.4 show representative values of hydraulic conductivities for various sedimentary materials (Domineco and Schwartz, 1997; Fetter, 2001). The results of slug testing in the Okanagan Valley fall comfortably within the ranges of accepted values published in the reference literature. The results are a good first-order approximation, but it is important to realise that slug testing is

Table 3.2 Summary table of slug test analysis from observation wells in the Okanagan Valley.

Unconfined Wells

Observation Well No.	Analysis method	Calculated conductivity values, K (m/s)						Average (m/s)	Aquifer description
		Slug-in 1	Slug-in 2	Slug-in 3	Slug-out 1	Slug-out 2	Slug-out 3		
96	Bouwer & Rice (manual)	1.14E-05	1.25E-05	1.11E-05	9.91E-06	9.62E-06	9.98E-06	1.08E-05	silty clay
	Bouwer & Rice	1.18E-05	1.27E-05	1.28E-05	1.08E-05	3.42E-07	1.17E-05	1.00E-05	
101	Bouwer & Rice	5.26E-06	4.94E-06	4.06E-06	2.98E-06	3.85E-06	2.83E-06	3.99E-06	sand & gravel
105	Bouwer & Rice	9.17E-07	4.71E-07	X	2.36E-07	4.42E-07	X	5.17E-07	silty clay, some gravel
162	Bouwer & Rice	6.39E-07	X	X	X	X	X	6.39E-07	bedrock
172	Bouwer & Rice	7.97E-05	9.01E-05	9.67E-05	5.87E-05	5.80E-05	5.27E-05	7.27E-05	gravel
174	Bouwer & Rice	1.93E-03	1.16E-04	1.36E-04	4.60E-03	3.83E-03	3.84E-03	2.41E-03	pebbly gravel
180	Bouwer & Rice	1.12E-04	4.51E-05	4.28E-05	4.35E-05	4.57E-05	2.87E-04	9.60E-05	fine-med sand
282	Bouwer & Rice	4.37E-03	9.22E-03	7.68E-03	4.66E-03	1.19E-02	8.48E-03	7.72E-03	sand & gravel
356	Bouwer & Rice	8.26E-05	6.21E-05	5.71E-05	7.31E-05	4.69E-05	2.06E-05	5.71E-05	silt, sand & gravel

Confined Wells

Observation Well No.	Analysis method	Calculated conductivity values, K (m/s)						Average (m/s)	Aquifer description
		Slug-in 1	Slug-in 2	Slug-in 3	Slug-out 1	Slug-out 2	Slug-out 3		
118	Butler (inertial effects)	7.24E-03	1.17E-02	1.03E-02	9.34E-03	8.13E-03	1.26E-02	9.89E-03	sand & gravel
119	Hvorslev (manual)	9.80E-05	1.11E-04	1.15E-04	7.23E-05	7.13E-05	6.41E-05	8.86E-05	coarse sand
	Hvorslev	4.70E-04	4.47E-04	5.55E-04	3.92E-04	3.09E-04	3.73E-04	4.24E-04	
	Cooper et al. (manual)	1.17E-04	4.78E-05	4.37E-05	4.54E-05	4.76E-05	2.90E-04	9.86E-05	
	Cooper et al.	4.13E-05	7.55E-05	2.90E-05	4.93E-05	4.74E-05	3.93E-05	4.70E-05	
154	Hvorslev	2.96E-04	3.13E-04	3.48E-04	3.65E-04	3.56E-04	3.70E-04	3.41E-04	silty sand & clay
	Cooper et al.	1.18E-04	4.22E-04	2.98E-04	5.03E-04	4.88E-04	4.94E-04	3.87E-04	
236	Hvorslev	3.16E-03	3.29E-03	3.30E-03	4.38E-03	4.82E-03	4.73E-03	3.95E-03	sand & gravel
	Cooper et al.	3.12E-03	3.24E-03	3.25E-03	4.31E-03	4.74E-03	4.66E-03	3.89E-03	

especially sensitive to the amount of development that has occurred in the well. The condition is very applicable to observation wells because they are not subject to regular pumping and may remain relatively undisturbed for long periods of time. It is also important to consider that slug testing is practically a point sample of the hydraulic conductivity for the whole aquifer, whereas a pumping test determination of hydraulic conductivity is a larger sample of the hydraulic conductivity value.

Table 3.3 Representative values of hydraulic conductivity for sedimentary materials (Domineco and Schwartz, 1997).

Material	Hydraulic Conductivity (m/s)
Gravel	$3 \times 10^{-4} - 3 \times 10^{-2}$
coarse sand	$9 \times 10^{-7} - 6 \times 10^{-3}$
medium sand	$9 \times 10^{-7} - 5 \times 10^{-4}$
fine sand	$2 \times 10^{-7} - 2 \times 10^{-4}$
silt	$1 \times 10^{-9} - 2 \times 10^{-5}$
till	$1 \times 10^{-12} - 2 \times 10^{-6}$
clay	$1 \times 10^{-11} - 4.7 \times 10^{-9}$

Table 3.4 Ranges of hydraulic conductivities for unconsolidated sediments (Fetter, 2001).

Material	Hydraulic Conductivity (m/s)
Well-sorted gravel	$10^{-4} - 10^{-2}$
Well-sorted sands, glacial outwash	$10^{-5} - 10^{-3}$
Silty sands, fine sands	$10^{-7} - 10^{-5}$
Silt, sandy silts, clayey sands, till	$10^{-8} - 10^{-6}$
Clay	$10^{-11} - 10^{-8}$

4. CLIMATE ANALYSIS

4.1. CLIMATE DATA

Environment Canada supplied daily climate data for the Okanagan region (Appendix C). In addition, climate normals were extracted from the Environment Canada website (http://www.climate.weatheroffice.ec.gc.ca/Welcome_e.html) and used to describe the climate at nine locations: Osoyoos, Oliver, Penticton, Summerland, Peachland, Kelowna, Winfield, Oyama and Vernon.

Graphs created for each location show the mean monthly rainfall, snowfall and temperature (Figure 4.1, Figure 4.2). The Osoyoos West climate station is the most southern climate station, and the Vernon Coldstream Ranch climate station is the most northern station. The climate at each station represents approximate end-members for climate within the Okanagan valley. In Osoyoos, the mean annual temperature is 10.1°C with a mean monthly maximum temperature of 29.2°C occurring in July, and a mean monthly minimum of 1.0°C in January. In Vernon, the mean annual temperature is 7.4°C with a mean monthly maximum temperature of 26.6°C occurring in July, and a mean monthly minimum of -8.1°C in January. Osoyoos receives an average of 317.6 mm of precipitation annually, with 15.6 % (49.6 cm) as snowfall. Vernon receives an average of 356.5 mm of precipitation annually, with 35.9 % (127.9 cm) as snowfall. Figure 4.3 compares the mean annual precipitation and temperature for all stations in the Okanagan.

Figure 4.1 Climate normals for the Osoyoos West (1125865) climate station.

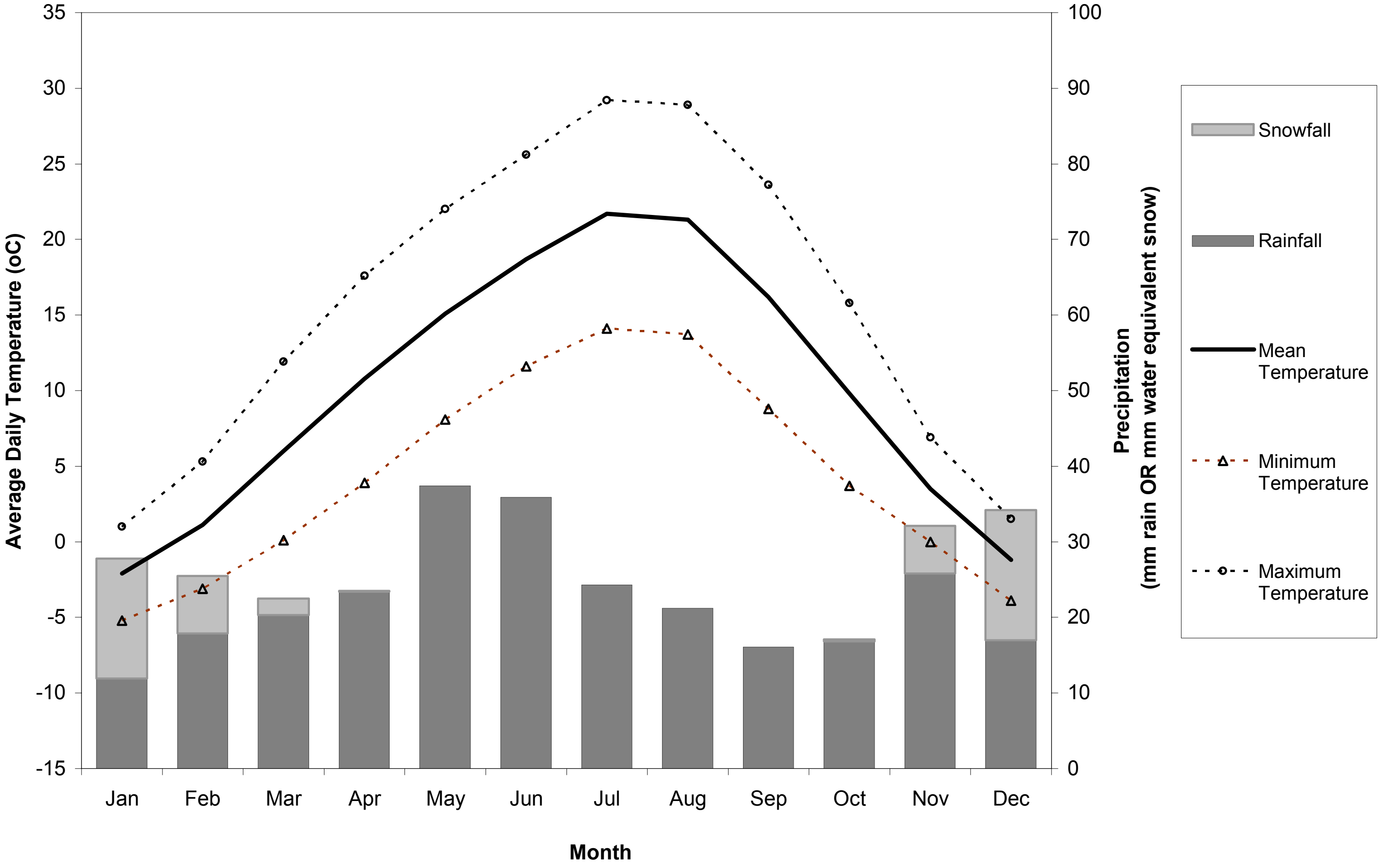


Figure 4.2 Climate normals for the Vernon Coldstream Ranch (1128551) climate station.

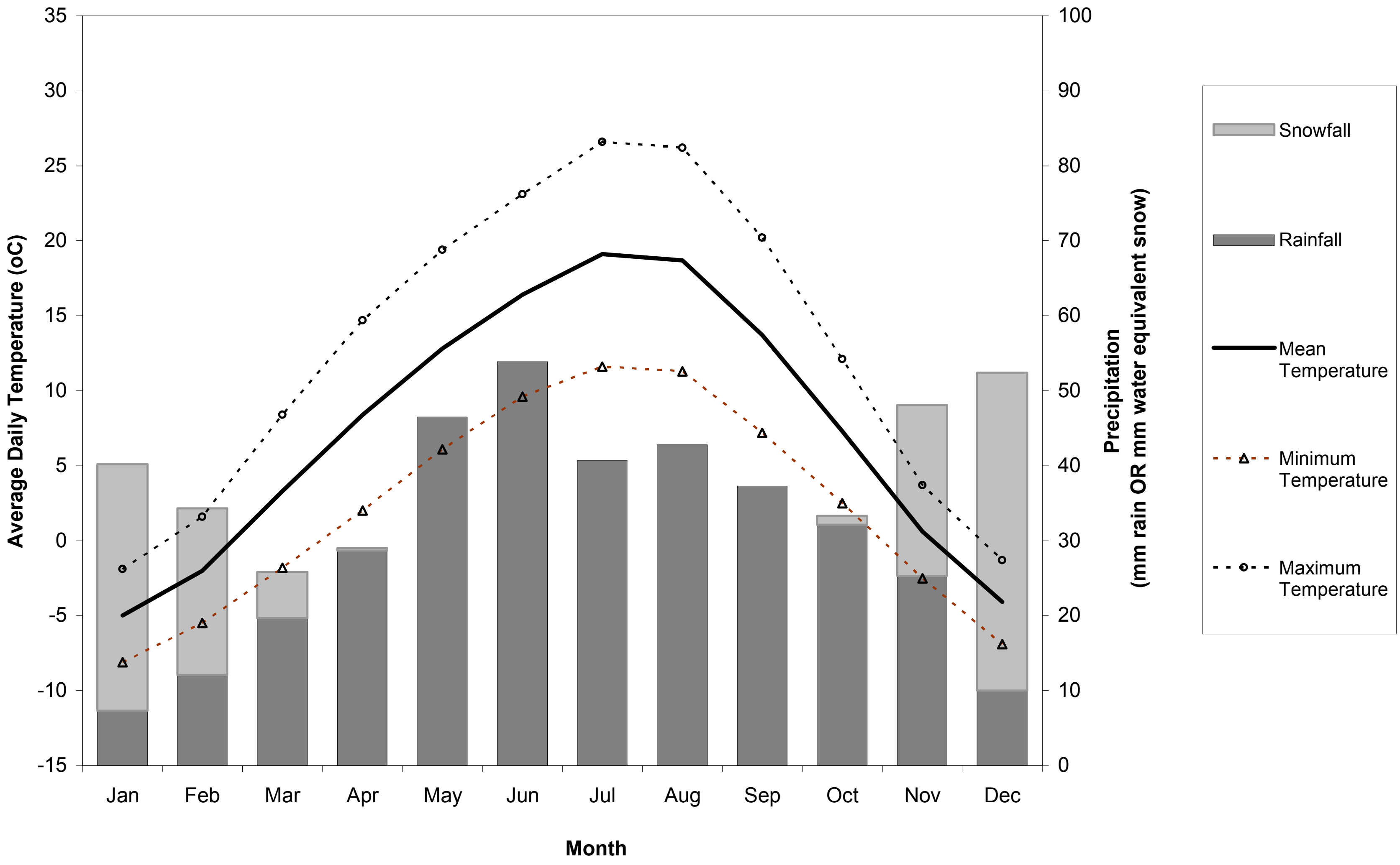
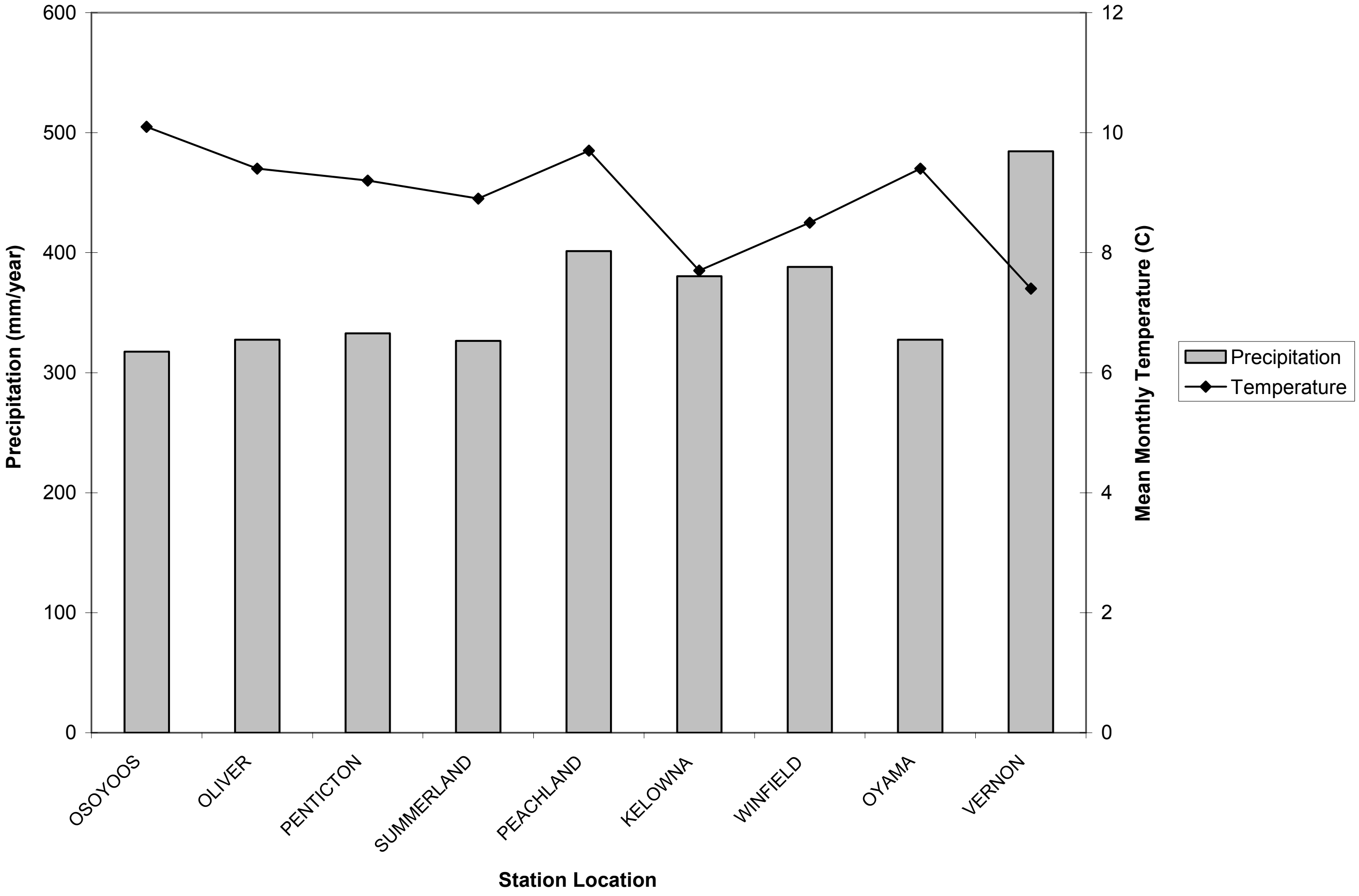


Figure 4.3 Mean annual precipitation and temperature for all stations in the Okanagan valley. Stations arranged south to north.



4.2. CLIMATIC TRENDS IN THE OKANAGAN BASIN

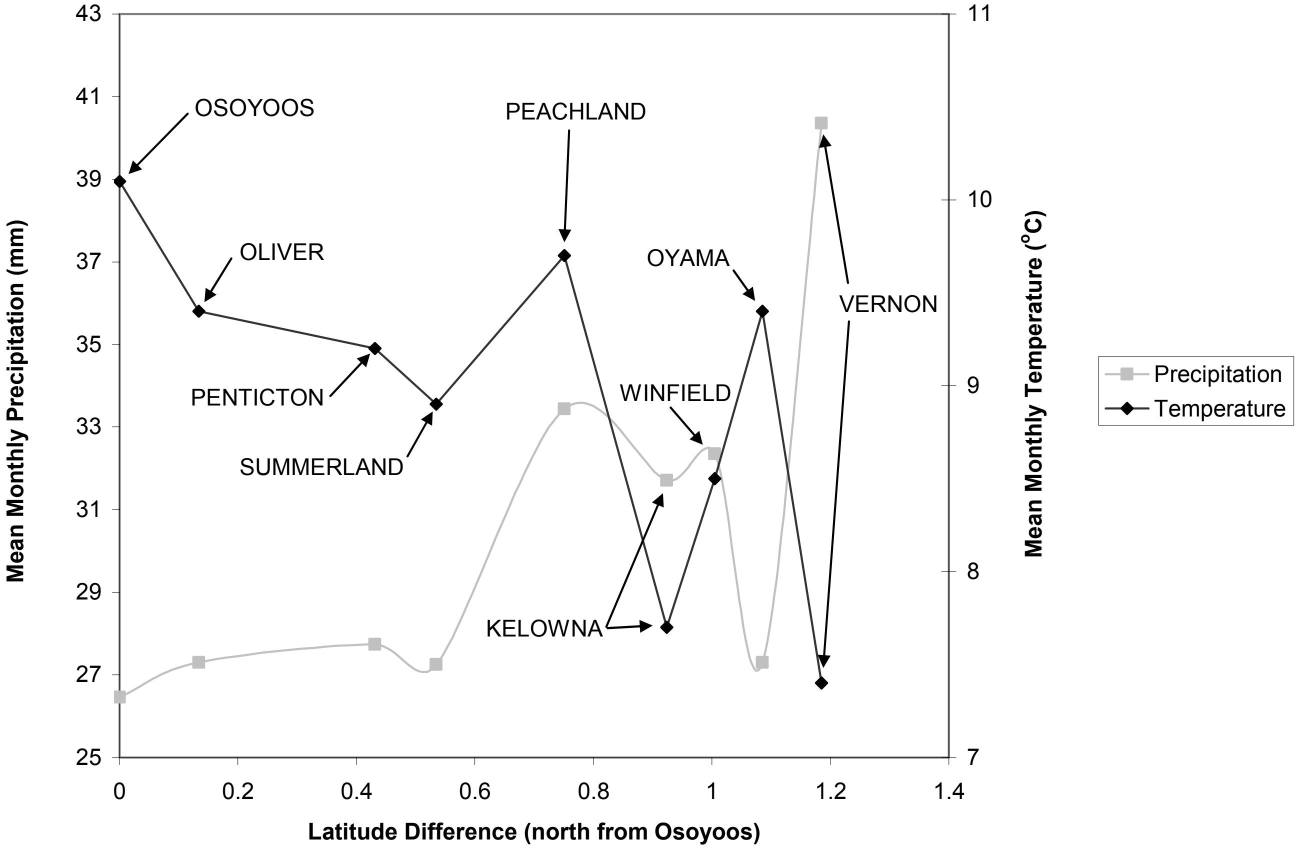
Figure 4.4 shows mean monthly temperature plotted against distance up the valley, using Osoyoos as the reference. There is a general trend for temperature to decrease up the valley. The trend becomes more apparent when Peachland and Oyama are removed from the plot. Peachland and Oyama may show temperatures that deviate from the overall trend because of differences in elevation between stations, or localized weather patterns related to topography. The mean monthly temperature ranges from 10.1 °C in Osoyoos to 7.4 °C in Vernon.

Figure 4.4 also shows mean monthly precipitation plotted against distance up the valley, using Osoyoos as the reference. There is a general trend for precipitation to increase up the valley. Again, the trend is more clear with Peachland and Oyama omitted from the analysis. The mean monthly precipitation ranges from 26.5 mm in Osoyoos to 40.4 mm in Vernon.

4.3. CUMULATIVE PRECIPITATION DEPARTURE

Cumulative precipitation departure (CPD) is a climate analysis technique that can be used to assess water level fluctuations in observation wells completed in shallow unconfined aquifers (Kohut and Zubel, no date*)*. The CPD method involves calculating the difference between monthly precipitation and the mean monthly precipitation for a given historic period. A strong correlation between a CPD curve and a hydrograph indicates

Figure 4.4 Trends in temperature and precipitation heading north in the Okanagan valley using Osoyoos as the reference station.



that precipitation has a major influence on water level at that well. A poor correlation indicates that the water level is controlled by another factor, such as a nearby river or anthropogenic influences (e.g., groundwater withdrawal).

The first step in a CPD analysis is to calculate the monthly mean precipitation for the longest period possible. Data from a single climate station, or a station nearby to an observation well, should be used because precipitation can vary dramatically with elevation and latitude differences. The second step involves subtracting the actual precipitation values for each month from the monthly mean. The cumulative sum of the differences is plotted against time to make the CPD curve. Figure 4.5 shows an example of a CPD curve for climate stations in Vernon. The peaks and troughs of the hydrograph for observation well #180 may not exactly match those on the CPD curve; however, the general timing of the larger trends are similar. The relationship between precipitation and water level may be stronger if the climate station was located closer to the observation well. The water level in observation well #180 is also affected by pumping wells on the same property. The effect of the pumping wells is most evident in during the summer months when the water level makes an exaggerated dip. If the interference caused by the pumping wells could be removed, the correlation would be stronger.

Figure 4.6 shows a clear example of observation wells with water tables that do not appear to be influenced by precipitation. Water level data from the wells shows a much higher frequency fluctuation and no dependences on precipitation trends. The result is expected since both observation wells are located within orchards.

Figure 4.5 Hydrograph for observation well #180 and a cumulative precipitation departure curve compiled from Vernon climate stations.

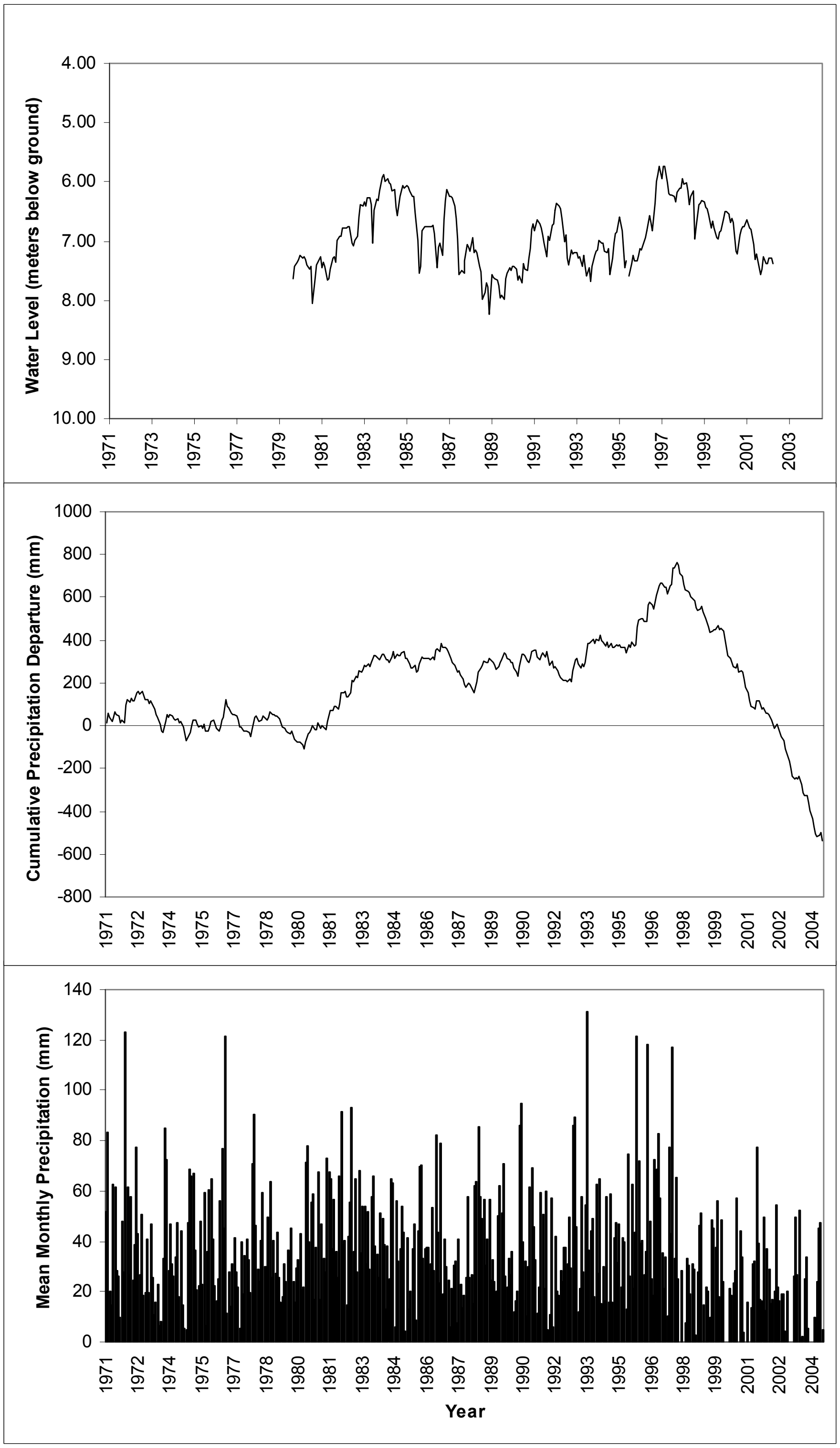
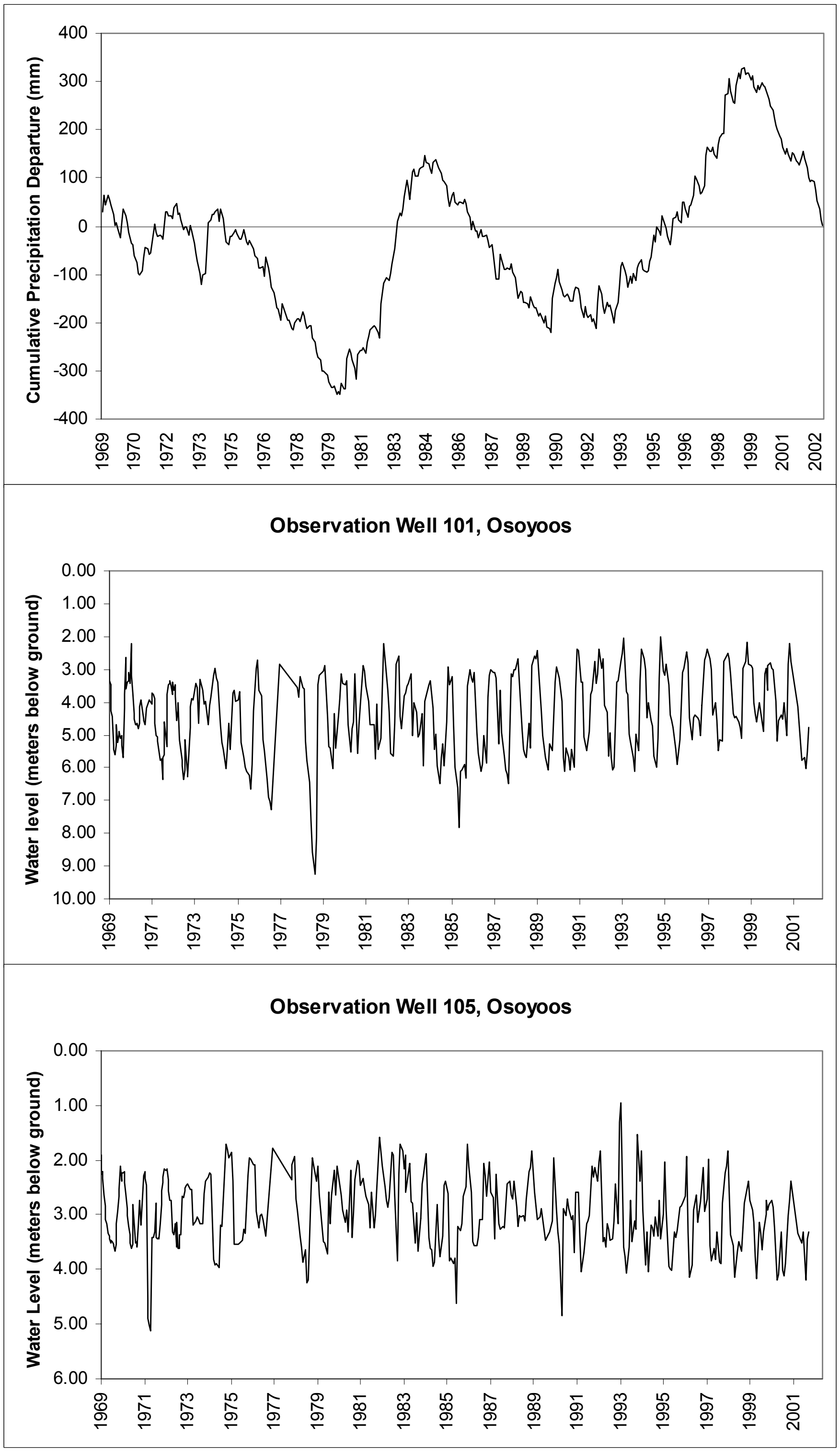


Figure 4.6 Hydrograph for observation wells #101 and #105, and the cumulative precipitation departure curve for Osoyoos West (1125865) climate station.



Observation Well 101, Osoyoos

Observation Well 105, Osoyoos

The water table in the vicinity of the orchards likely responds to irrigation patterns associated with the fruit crops.

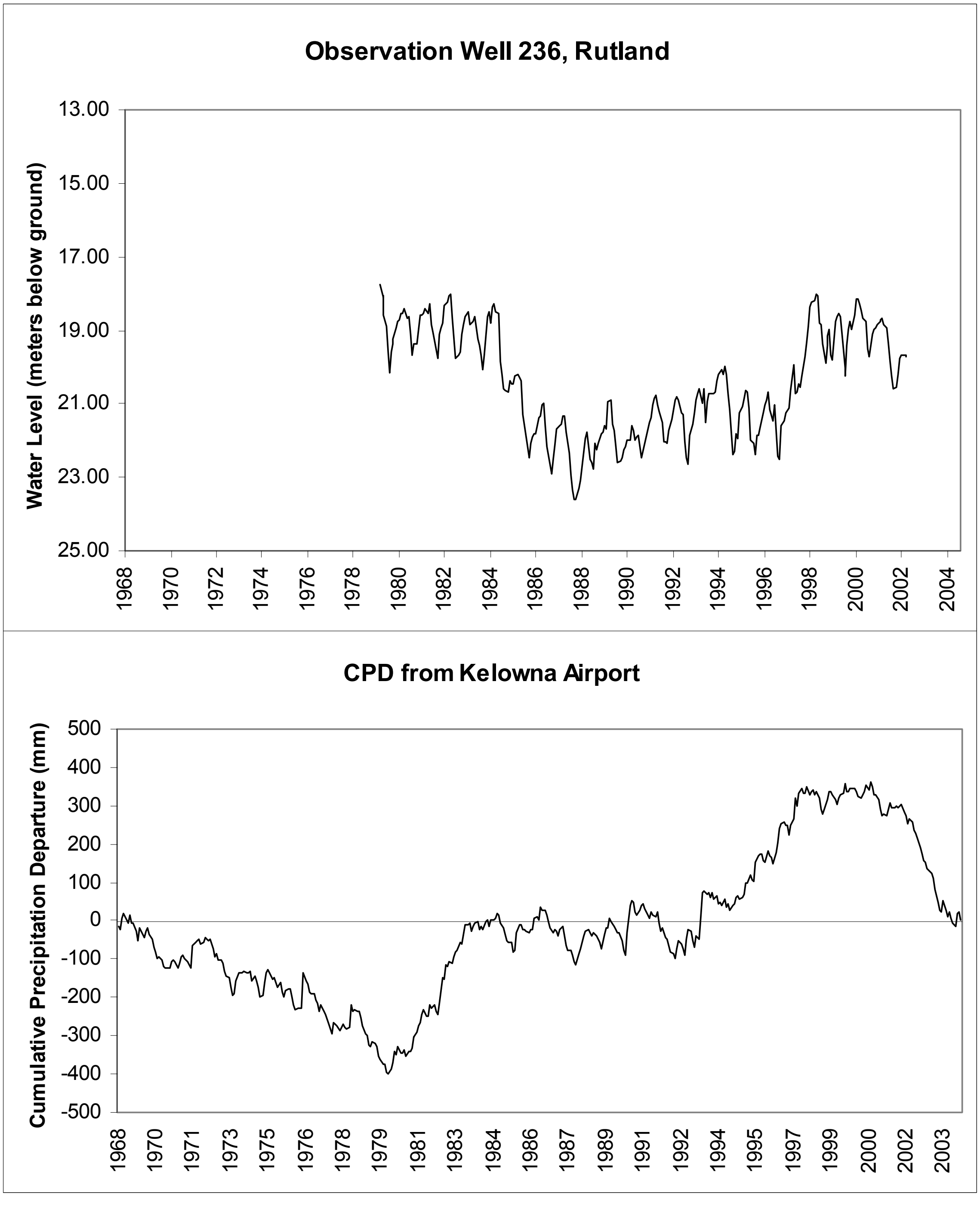
4.4. RESULTS

Using the CPD method of analysis, it was determined that six of the 13 well hydrographs showed a good correlation with their corresponding CPD curve. These include observation wells #118, #119, #162, #180, #236 and #282. Even wells under the direct influence of pumping activities (e.g., observation wells #162, #180 and #236) show a strong correlation to precipitation data despite drawdown anomalies created by pumping (Figure 4.7). The six wells that show a strong correlation to precipitation qualify for recharge estimation using the water table fluctuation method (WTF). A summary of CPD comparisons is presented in Table 4.1.

Table 4.1 Summary of observation wells directly influenced by precipitation.

Obs Well No.	**Location**	**Recharged by Precipitation**
118	Armstrong	Yes
119	Armstrong	Yes
162	Kalawoods	Yes
180	Eagle Rock	Yes
236	Rutland	Yes
282	Myer's Flats	Yes
96	Osoyoos	No
101	Osoyoos	No
105	Osoyoos	No
154	Summerland	No
172	Oyama	No
174	Kalawoods	No

Figure 4.7 Observation well #236 shows a good correlation with the cumulative precipitation departure curve despite being under the influence of a nearby pumping well.


Observation Well 236, Rutland

CPD from Kelowna Airport

5. RECHARGE ESTIMATION

5.1. RECHARGE ESTIMATION

Fluctuations in groundwater levels can be used to estimate recharge, an essential component of water budgets. Freeze and Cherry (1979) define recharge as "the entry into the saturated zone of water made available at the water-table surface, together with the associated flow away from the water table in the saturated zone." A recharge event, such as rainfall, occurs when the amount of water percolating through the soil exceeds the ability of the soil to withhold water against the force of gravity. Change in subsurface storage, as groundwater in the saturated zone, is equal to recharge plus groundwater flow into the basin minus baseflow, evapotranspiration of groundwater, and groundwater flow out of the basin (Healy and Cook, 2002; Domenico and Schwartz, 1997; Schict and Walton, 1961). The equation can be rearranged in terms of recharge:

$$R = \Delta S^{gw} + Q^{bf} + ET^{gw} + Q^{gw}_{out} - Q^{gw}_{in} \qquad [5.1]$$

where:

R = recharge [mm/year];

ΔS^{gw} = change in subsurface storage [mm/year];

Q^{bf} = baseflow [mm/year];

ET^{gw} = evapotranspiration from groundwater [mm/year];

$Q^{gw}_{out} - Q^{gw}_{in}$ = net subsurface flow out the basin [mm/year].

Baseflow describes groundwater discharge to streams and springs. Baseflow is a time dependent parameter that increases as stream discharge exponentially decays in the absence of a source (Domenico and Schwartz, 1997). Groundwater recession is the baseflow component of streams that remove groundwater from storage. Pumping rates, included in the term $Q_{out}^{gw} - Q_{in}^{gw}$ can change over hours, days or seasons. Rainfall intensity, duration and persistence influence the rate and timing of percolation fronts reaching the water table. The groundwater level will always reflect the net influence of input or withdrawal to the system over.

The seeming complexity of recharge dynamics can be reduced by making some semantic definitions on the use of recharge. The Water-Table Fluctuation (WTF) method assumes that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table level (Healy and Cook, 2002). The assumption works best over short times (e.g., hours to days) for discreet recharge events where water enters directly into storage, and all other components of Equation 5.1 are zero. Recharge is the change in water level from the hydrograph peak to the extension of the recession curve below the peak divided by the time between the precipitation event and the water level rise (Figure 5.1):

$$R = S_y \frac{dh}{dt} = S_y \frac{\Delta h}{\Delta t} \qquad [5.1]$$

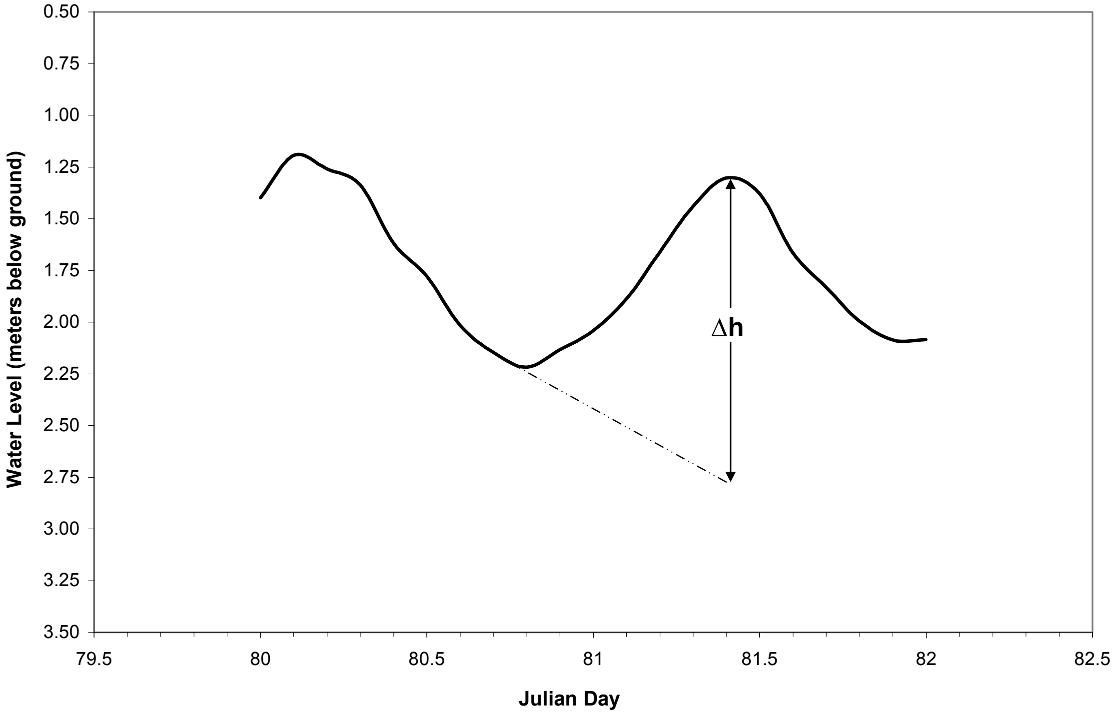
where:

S_y = specific yield [dimensionless];

h = water table height [mm];

t = time.

Figure 5.1 A hypothetical water table rise after a discreet rainfall event. The dashed line represents the extrapolated recession curve, and a possible source of uncertainty when calculating recharge.



To determine total or "gross" annual recharge, Equation 5.1 would have to be applied to every individual water level rise during the study period. For periods longer than hours or days, the assumptions in Equation 5.1 begin to breakdown. If the rate at which groundwater is removed from the system is comparable to the rate of recharge, the result may be misleading or wrong. When the method is used over long time periods (e.g., seasons or years), it produces an estimate of change in subsurface storage (ΔS^{gw}), or "net" recharge. An estimation of *net* recharge, or *net* recharge rates, seems more appropriate to the data produced by most wells in the observation well network. As of August 2004, only two observation wells (#54 and #264) were known to have daily data (Paul Whitfield, pers. comm.), and they were not included in the study due to access issues and vandalism.

An adaptation to Equation 5.1, will be used here for estimating annual recharge rate based on monthly data (Ministry of Environment, 1986). The equation is essentially the same as Equation 5.1 except that it is not necessary to estimate the extension of the recession below the peak. Simply, the rate of decline of water level through recession is added to the observed increase in water level according to Equation 5.2a. Upon simplification, the recharge rate is estimated by the sum of the rate of water level decline and water level rise multiplied by the specific yield (S_y) (Equation 5.2b and Figure 5.2):

$$R = \frac{S_y \Delta h_1}{\Delta t_1} + \left(\frac{S_y \Delta h_0 \Delta t_1}{\Delta t_0} \right) \left(\frac{1}{\Delta t_1} \right) \qquad [5.2a]$$

$$\mathrm{R} = \mathrm{S_y} \left(\frac{\Delta \mathrm{h}_1}{\Delta \mathrm{t}_1} + \frac{\Delta \mathrm{h}_0}{\Delta \mathrm{t}_0} \right) \qquad [5.2b]$$

where:

S_y = unconfined storativity, or specific yield [dimensionless];

Δh_o = water level decline (m);

Δh_1 = water level rise (m);

Δt_o = period of water level decline (months or years);

Δt_1 = period of water level rise (months or years).

The unconfined storativity is approximately equal to the specific yield. The value of S_y represents the most significant source of uncertainty. Specific yield is defined as the difference between porosity and specific retention, the volume of water retained by a rock after drained by gravity. In a sense, specific yield is a storage term. The uncertainty associated with specific yield estimates, and subsequent recharge estimates, is related to the time dependence of yield values. For example, it could take several years to experimentally determine specific yield values for sediments with grain sizes smaller than fine sand (Healy and Cook, 2002). Table 5.1 lists the maximum and minimum specific yield values (Johnson, 1967) that are suitable for calculating recharge values.

Figure 5.2 The water table fluctuation method (WTF) used on the hydrograph of observation well # 236, Rutland, BC.

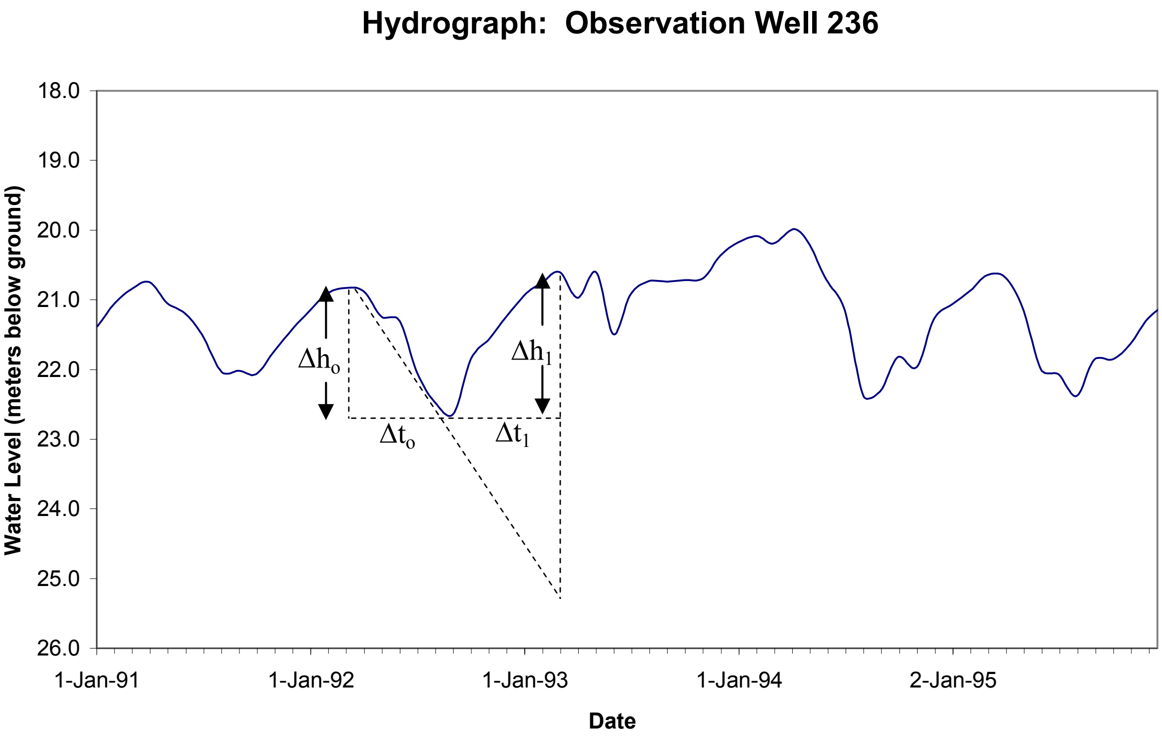


Table 5.1 Values of specific yield compiled from Johnson (1967).

Texture	Average Specific Yield	Minimum Specific Yield	Maximum Specific Yield
Clay	0.02	0	0.05
Silt	0.08	0.03	0.19
Sandy clay	0.07	0.03	0.12
Fine sand	0.21	0.1	0.28
Medium sand	0.26	0.15	0.32
Coarse sand	0.27	0.2	0.35
Gravelly sand	0.25	0.2	0.35
Fine gravel	0.25	0.21	0.35
Medium gravel	0.23	0.13	0.26
Coarse gravel	0.22	0.12	0.26

There is some subjectivity when applying the WTF method to hydrographs. The water level does not always follow a predictable pattern of spring peaks and summer troughs. The hydrograph of observation well #118 shows periods between peaks and troughs that typically exceed one year (Figure 5.3). The water level in observation well #118 coincides well with the cumulative precipitation departure curve, but may be responding to long-term climatic trends rather than yearly precipitation (e.g., Pacific Decadal Oscillation). The well screen is also situated quite deep (>1000 feet), and the wetted front of descending water tends to disperse over longer travel distances. Observation well #118 is completed in a confined aquifer where water level trends may be more closely linked to long-term climatic change than short-term precipitation events.

Observation wells that are in close proximity to pumping wells may produce recharge estimates that are misleading. Water pumped from the aquifer reduces the yearly maximum and minimum water level. Hydrographs with deep troughs, sometimes shaped like a cone of depression, can be an indication of pumping activity (Figure 5.4). The effects of pumping are visible in observation wells #180 and #236. The presence of municipal scale pumping systems within less than 50 m and 500 m of the wells, respectively, was confirmed during slug testing. The WTF method (Equation 5.2) will overestimate recharge rates in wells that are under the direct influence of pumping.

5.2. RESULTS

When applying the WTF method (Equation 5.2), a representative period on the hydrograph was selected to determine an estimate of recharge rate and *net* recharge. The *net* amount of annual recharge was determined by the difference between any two peaks a year apart, usually during groundwater level maximums in the spring. In some cases, such as observation well #162, there are multiple peaks within the span of a year. Table 5.2 summarizes estimates of recharge rate and net recharge for the observation wells that are considered to be primarily recharged by precipitation (Table 5.2). Observation wells #118, #119 and #236 are confined wells and cannot be recharged

Figure 5.3 Hydrograph of observation well #118 possibly shows water level response to long-term climate changes.

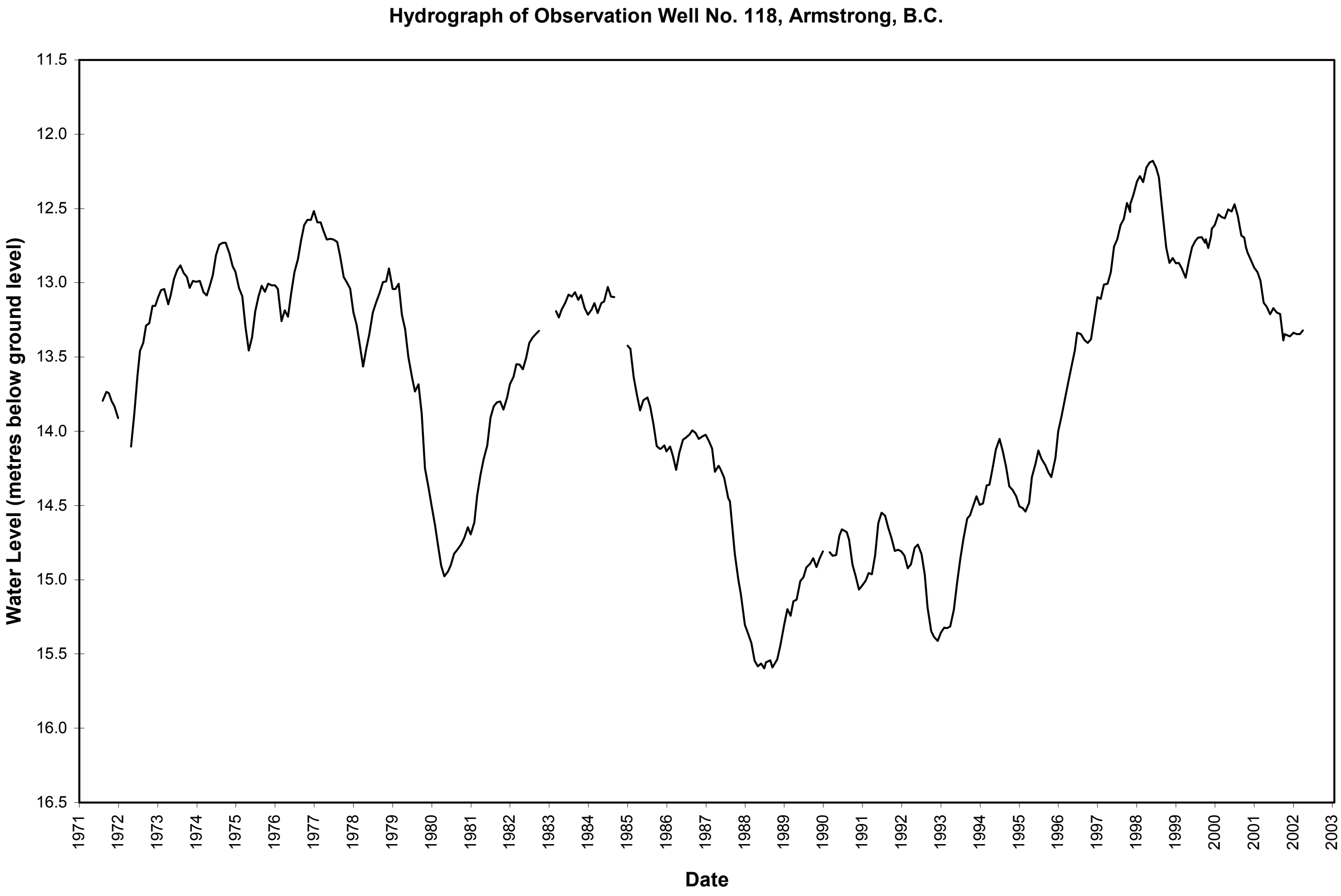
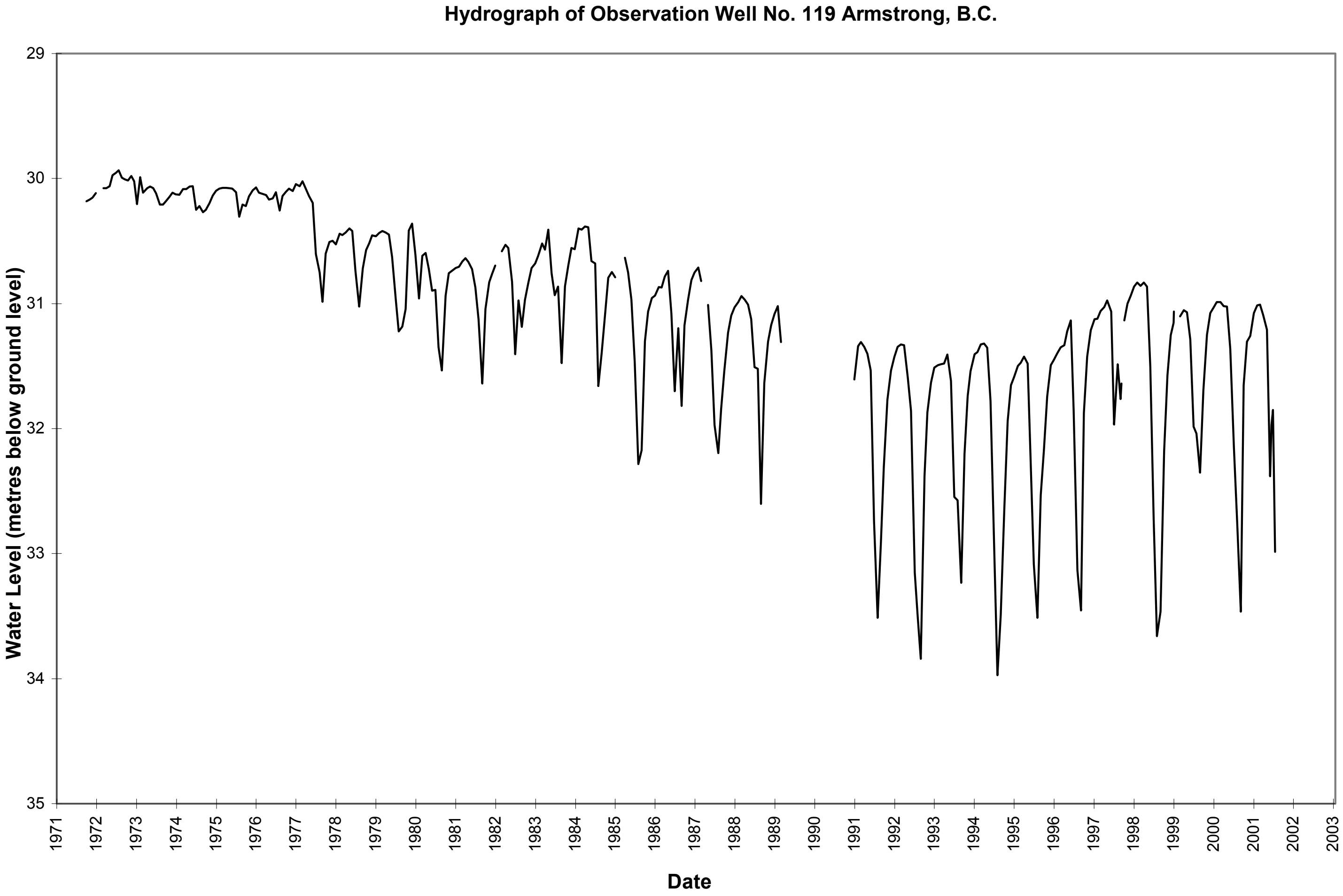


Figure 5.4 Hydrograph of observation well #119 shows decreased water level minimums and maximums due to pumping nearby.



directly by precipitation, but nonetheless have been analyzed and included in Table 5.1 for comparison. Observation well #162 has been omitted from this analysis on the basis that it is completed in shale bedrock. Groundwater flow mechanisms are different in bedrock "aquifers" than in unconsolidated sediments. Groundwater may move through bedrock along fractures or joints, which are not accurately described by the specific yield associated with the porosity.

Table 5.2 Summary table of estimates for recharge rate and net recharge.

Observation Well Number	Recharge Period	h_o (m)	t_o (months)	h_1 (m)	t_1 (months)	Aquifer Type	S_y - Low	S_y - High	Recharge Rate - Low (m/month)	Recharge Rate - High (m/month)	Net Recharge (m)	Average Rate - Low (m/month)	Average Rate - High (m/month)
118	1977-1979	1.046	14.9	0.659	8.0	sand and gravel	0.20	0.35	0.03	0.05	-0.387	0.029	0.051
	1990-1991	0.379	6.3	0.469	7.0	sand and gravel	0.20	0.35	0.03	0.04	0.090		
	1994-1995	0.489	7.9	0.409	3.9	sand and gravel	0.20	0.35	0.03	0.06	-0.080		
	1998-1999	0.788	10.1	0.274	5.0	sand and gravel	0.20	0.35	0.03	0.05	-0.514		
119	1974-1975	0.211	3.1	0.189	8.9	coarse sand	0.20	0.35	0.02	0.03	-0.022	0.114	0.200
	1982-1983	0.878	3.0	0.997	9.9	coarse sand	0.20	0.35	0.08	0.14	0.119		
	1994-1995	2.653	4.0	2.548	8.0	coarse sand	0.20	0.35	0.20	0.34	-0.105		
	2000-2001	2.476	6.2	2.457	5.9	coarse sand	0.20	0.35	0.16	0.29	-0.019		
180	1978-1979	1.088	8.0	0.679	5.0	fine to med sand	0.10	0.32	0.03	0.09	-0.409	0.024	0.075
	1991-1992	0.62	5.0	0.902	6.1	fine to med sand	0.10	0.32	0.03	0.09	0.282		
	1999-2000	0.63	8.9	0.451	5.0	fine to med sand	0.10	0.32	0.02	0.05	-0.179		
	2000-2001	0.722	6.1	0.596	5.0	fine to med sand	0.10	0.32	0.02	0.08	-0.126		
236	1991-1992	1.317	6.0	1.236	5.1	sand and gravel	0.20	0.35	0.09	0.16	-0.081	0.128	0.224
	1992-1993	1.805	6.0	2.030	6.0	sand and gravel	0.20	0.35	0.13	0.22	0.225		
	1994-1995	2.389	3.9	1.721	6.9	sand and gravel	0.20	0.35	0.17	0.30	-0.668		
	1995-1996	1.731	5.0	1.707	7.0	sand and gravel	0.20	0.35	0.12	0.21	-0.024		
282	1994-1995	1.057	7.9	3.842	6.0	sand and gravel	0.20	0.35	0.16	0.27	2.785	0.181	0.318
	1995-1996	1.345	7.1	3.815	4.0	sand and gravel	0.20	0.35	0.23	0.40	2.470		
	1996-1997	3.068	7.1	4.215	5.9	sand and gravel	0.20	0.35	0.23	0.40	1.147		
	1997-1998	3.599	7.1	1.074	4.7	sand and gravel	0.20	0.35	0.15	0.26	-2.525		
	1998-1999	2.369	7.1	1.667	4.0	sand and gravel	0.20	0.35	0.15	0.26	-0.702		

6. CONCLUSIONS

- The hydraulic conductivities determined from slug testing in the Okanagan Valley range between ~10^{-7} m/s for silty clay aquifers, and ~10^{-3} m/s for sand and gravel aquifers. The values obtained from slug testing correspond well with published values of hydraulic conductivities (Fetter, 2001; Domenico and Schwartz, 1997). The results justify the usefulness of slug testing as an efficient and inexpensive method of making first order approximations about the hydraulic conductivity in the immediate vicinity of the well. Slug testing is similar to a point sample of conductivity in the aquifer where as a pumping test could provide an average value of conductivity for a much larger area. Where the nature of the aquifer (e.g., degree of heterogeneity and anisotropy) is well understood, the k-values from slug testing may be expanded to a larger area. The corollary is to perform many slug tests on many wells completed in the same aquifer. This would require a significant expansion in the observation well network, or access to wells that already exist.

- The cumulative precipitation departure (CPD) method indicated that six wells in the study area are recharged directly by precipitation. The CPD method was applied in a historical sense within this study. Once an aquifer is characterized as being primarily recharged by precipitation, groundwater level increases can be predicted from precipitation events. The CPD method may not evaluate the significance of other recharge sources such as lakes, rivers and interbasin flow, which may also be related to climatic trends intrinsic in precipitation records. A comprehensive study (e.g., hydrogeological, hydrological, limnological, climatic, etc.) should be undertaken to determine whether groundwater depletion is a result of over-withdrawal or climatic trends.

- Some skepticism exists within the author about the usefulness of the recharge rate estimates calculated using the water-table fluctuation (WTF) method. Of the 12 wells in the study area, only one well fits the criteria for assumptions inherent to the WTF method. Observation well #282, located in Myer's Flats, is completed in an unconfined aquifer with a shallow water table that shows a good correlation with the CPD curve - a good candidate for the WTF method. The climate station used in the CPD comparison, located in Oliver, reports a mean monthly precipitation of 28.9 mm between 1994 and 1999 (5 years). The recharge rate determined by the WTF method indicates that the aquifer receives between 181 mm (low S_y) and 318 mm (high S_y) per month. A significant discrepancy exists in that recharge is higher than precipitation, and it is unlikely that this discrepancy can be accounted for by the difference in elevation between the observation well and the climate station.

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