Chevron Environmental Management Company

Aquifer Testing Work Plan

Former Unocal Edmonds Terminal

11720 Unoco Road

Edmonds, Washington

January 25, 2011

ARCADIS

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Former Unocal Edmonds Terminal
11720 Unoco Road
Edmonds, Washington

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Chevron Environmental Management Company

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Figures

Appendices

Acronyms and Abbreviations

ARCADIS	ARCADIS U.S., Inc
bgs	below ground surface
BSNF	BNSF Railway Company
Chevron	Chevron Environmental Management Company
CSM	Conceptual Site Model
ft	foot (feet)
gal	gallon(s)
gpm	gallon(s) per minute
LNAPL	Light Non-Aqueous Phase Liquids
SOP	Standard Operating Procedure
Unocal	Union Oil Company of California

1. Introduction

On behalf of Chevron Environmental Management Company (Chevron), ARCADIS U.S., Inc. (ARCADIS) has prepared this aquifer testing work plan for the former Unocal (Union Oil Company of California) terminal located at 11720 Unoco Road in Edmonds, Washington (the Site). The Site and surrounding area are shown on **Figure 1**. This work plan summarizes hydraulic evaluation activities that will be completed as part of an evaluation of remediation alternatives in a Feasibility Study. These activities will also help define possible changes to site hydrogeology post- 2007/2008 interim action, and to better understand the connectivity of groundwater to local surface water features.

This workplan includes the following hydraulic evaluation activities:

- **Tidal study.** A tidal study will be completed to gather information regarding short-term, transient gradients at the Site and to improve understanding of the surface water-groundwater interactions at the Site. This information will be used to update the Conceptual Site Model (CSM) and inform the evaluation of the additional remedial alternatives.

- **Aquifer tests**. Aquifer tests will be performed to update and improve understanding of hydraulic conductivity of saturated material and the groundwater flow regime. Aquifer tests include short- and long-duration pumping tests and if necessary, slug tests.

1.1 Site Description

The Lower Yard occupies approximately 22 acres and lies east-southeast of BNSF Railway Company (BNSF) property, south of the Edmonds Marsh (also known as the Union Oil Marsh) and a drainage ditch (Willow Creek), and north of the Upper Yard. The site layout is shown on **Figure 2**.

At its nearest point (the southwest corner of the Lower Yard), the Lower Yard boundary is approximately 160 feet from the Puget Sound shoreline. Two detention basins (DB-1 and DB-2) are located along the north and northeast boundaries of the Lower Yard.

DB-1 borders Edmonds Marsh and Willow Creek and acts as a retention pond for overflow from DB-2 during storm events. DB-2 serves as a collection area from which site stormwater is discharged into Willow Creek.

Currently, a stormwater system consisting of 12 storm drains collects surface water runoff and discharges directly into DB-2 via gravity flow. From DB-2, stormwater is discharged into Willow Creek under an Industrial Stormwater General Permit (SO3-002953C), and excess stormwater is stored in DB-1. There are currently no permanent above ground structures at the site. A temporary storage shed is located along Unoco Road in the southern portion of the Lower Yard.

Previous structures in the Lower Yard included petroleum storage and transfer equipment (aboveground storage tanks and piping), two truck loading racks, several office buildings, a railcar loading/unloading station, a stormwater conveyance system including two 10,000-gallon stormwater detention tanks and two 500-gallon vapor recovery tanks, an air-blown asphalt plant, and an asphalt packaging warehouse.

Aerial photographs dated 1955 and 1967 show an extension of DB1 toward the asphalt plant. This extension was used for disposal of off-specification asphalt. An aerial photograph from 1976 shows the extension was filled in and DB2 constructed on top of it.

1.2 Site History

Unocal operated the bulk fuel terminal from 1923 to 1991. Fuel was brought to the terminal on ships, pumped to the storage tanks in the Upper Yard, and loaded from the tanks into rail cars and trucks for delivery to customers. In addition, an asphalt plant operated at the Lower Yard from 1953 to the late 1970s.

In 2001, Unocal conducted an Interim Action in the Lower Yard, removing light non-aqueous phase liquid (LNAPL) and petroleum-impacted soil and groundwater from four areas of the Lower Yard. The results of the 2001 Interim Action are summarized in *Lower Yard Interim Action As-built Report, Unocal Edmonds Terminal – Volume 1* (MFA 2002). Additional Interim Actions conducted in 2003 included soil excavations in the Southwest Lower Yard and Detention Basin No.1. The results of the 2003 Interim Action are summarized in *2003 Lower Yard Interim Action As-Built Report, Detention*

Basin No. 1, Southwest Lower Yard, Metals Area 3, and Storm Drain Line Excavations – Volume 1 (MFA 2004). Previous excavations are shown on **Figure 2**.

In June 2007, Unocal entered into an Agreed Order with the Washington Department of Ecology (DOE) to conduct an Interim Action in the Lower Yard (DOE 2007). Specific objectives of the Interim Action included:

- Removal of soil with petroleum impacts in excess of the soil remediation levels established for the Lower Yard
- Removal of LNAPL
- Extraction of groundwater that is in contact with LNAPL
- Removal of soil with arsenic concentrations in excess of the soil remediation levels within the Southwest Lower Yard

The 2007 Agreed Order Interim Actions were completed in two phases from July 2007 to April 2008 (Phase 1), and July 2008 to October 2008 (Phase II). Phase I Interim Action work consisted of the removal of 108,000 tons of petroleum impacted soil for offsite disposal, and the removal of approximately 9,700 gallons of light non-aqueous phase liquid (LNAPL). During Phase I construction activities approximately two million gallons of groundwater was also extracted, treated onsite, and discharged under a National Pollutant Discharge Elimination System Permit (NPDES) to Willow Creek. The complete results of the 2007 Phase I Interim Actions are summarized in *Phase I Remedial Implementation As-Built Report, Unocal Edmonds Bulk Fuel Terminal Lower Yard* (ARCADIS 2009). Phase II Interim Action work consisted of the removal of 14,825 tons of petroleum impacted soil for offsite disposal, and the removal of 131 gallons of LNAPL. Approximately 520,000 gallons of groundwater was extracted, treated onsite, and discharged to Willow Creek under a NPDES permit. Phase II construction activities also included the removal of 2,000 tons of impacted sediments, and subsequent restoration of approximately 420 feet of Willow Creek. The complete results of the 2008 Phase II Interim Action are summarized *in FINAL – Phase II Remedial Implementation As-Built Report, Unocal Edmonds Bulk Fuel Terminal Lower Yard* (ARCADIS 2010).

1.3 Geology

During the Phase I excavation (2007 to 2008), subsurface materials encountered from land surface to a depth of 8 to 15 feet below ground surface were silty sands with gravel and sandy silts with gravel. This material is fill placed after 1929 during the creation of the lower yard facility. Below the 1929 fill material a poorly graded sand formation of very fine to medium sand with fine gravel was encountered, which contains organic material such as beach debris, wood, and seashells, and is considered the native soil below the terminal. In many excavation areas throughout the Lower Yard there is a layer approximately 6 to 12 inches thick composed of sandy silt with large amounts of peat, wood debris, and decomposing vegetation. This layer was encountered at depths of 8 to 14 ft bgs, between the 1929 fill material, and the native soil, and is considered to be representative of the former marsh located at the Site.

The current lithology of the Lower Yard consists primarily of backfill material from the Phase I and Phase II Interim Action work (2007 to 2008). Excavations were backfilled with poorly graded coarse gravels to 6-inches above the water table, and continued to grade with a very fine to medium sand, trace silt, and coarse gravel. Below the excavation backfill material is a poorly graded sand formation of very fine to medium sand with fine gravel, which contains organic material such as beach debris, wood, and seashells, and is considered the native soil below the terminal.

2. Proposed Hydraulic Evaluation

The hydraulic investigation activities will be completed as part of an evaluation of potential remediation alternatives for the site in consideration of possible changes to site hydraulics post- 2007/2008 interim action. A tidal study will be completed to provide detailed understanding of surface water-groundwater interactions at the Site and short duration aquifer testing (“pumping tests”) will be completed to update and improve understanding of the hydraulic conductivity of saturated material at the Site.

2.1 Tidal Study

A tidal study will be completed prior to executing short-duration pumping tests. The tidal study will be performed to help gain a better understanding of tidal influences at the Site. The following tasks will be completed as part of the tidal study:

- Obtain background information about on-site water level influences prior to pumping tests, Improve understanding of short-term horizontal gradient changes

- Evaluate the potential for, and various properties of, flow gradient reversals onsite

- Measure and record salinity for improved understanding of transient salinity changes

If practically feasible, a two-week tidal study will be completed at “spring tide[1]”. Tide tables for the closest gauge to the Puget Sound for the year of 2011 are included in Appendix A. The tidal study will commence upon approval of workplan.

2.1.1 Transducer Locations

Transducers will be installed in monitoring wells MW-149R, MW-8R, MW-104, MW-518, MW-510, LM-2, MW-129R, MW-122 and MW-500 (**Figure 3**). These well locations were selected to represent the variety of fill and native materials at the Site. Also, these wells are located in areas where future extraction wells may be installed, so data collected by transducers will provide representative hydraulic conditions for those areas. Monitoring well MW-122 is a deeper well and will provide information on vertical gradients during tidal fluctuations in the northeastern part of the Site. Transducers will also be installed in upgradient monitoring wells MW-515 and MW-502. Data collected at these wells will be used to calculate the tidal signal attenuation across the site. A barometric pressure transducer will be installed above the expected high water level in a well for recording barometric pressure over the study period.

Pressure transducers will be installed at all existing staff gauge locations D1, D2, D3, D4, D5, and D6 (Figure 3). If it appears any location will present special difficulties for installing a pressure transducer, Ecology will be contacted for discussion of the impact of the lost data. The data-logging pressure transducers will be installed below the water level at a depth sufficient to measure the extreme lows and highs of water levels.

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[1] A “spring tide” refers to the period when the tidal range is at a relative maximum and does not refer to the season.

A stilling well will be installed in the Puget Sound adjacent to the Site for monitoring surface-water level changes due to tidal influence. The stilling well will be mounted on a dock or relatively protected area adjacent to the Site in the Puget Sound. The purpose of a stilling well is to “still” the water around the pressure transducer to monitor surface-water-level readings of the Puget Sound. Stilling the water reduces the scatter caused by wave action on the surface of the Puget Sound, however, the water inside the well must be able to fluctuate with rising or falling water levels. A slotted section of polyvinyl chloride pipe can be used, allowing water inside the stilling well to more quickly equalize to the changes in stage of the Puget Sound. Guidance for installation of a stilling well is provided in Appendix B. After the stilling well is installed it will be surveyed by a licensed surveyor. An access agreement for permission to install the stilling well will be required from the City of Edmonds.

2.1.2 Transducer Data Collection and Evaluation

Aqua Troll® 200 data-logging pressure transducers will be deployed in monitoring wells and the stilling well to record groundwater temperature, barometric pressure, salinity, and depth data in 10-minute intervals for a two-week period, starting one week prior to and extending one week after the maximum tidal range. The data-logging pressure transducers will be installed to approximately one foot above the bottom of the well. The length of the cable plus the transducer deployed in the well will be measured and recorded. Confirmatory water levels will be collected with a manual water level indicator the day after the transducers are deployed and twice after that, on a weekly basis, during the monitoring period along with manual staff gauge readings.

Data collected during the two-week pressure-transducer deployment will be used to calculate average horizontal hydraulic gradients, evaluate attenuation of tidal fluctuation effects on Site groundwater heads, and calculate tidal efficiency factor. The tidal efficiency factor is an indicator of the hydraulic connection of the aquifer materials with the tidally influenced surface water body. Higher tidal efficiency factors have indicated a greater hydraulic connection than lower values.

Downhole and re-usable equipment will be decontaminated prior to use at each location.

2.2 Aquifer Testing

Aquifer tests will be performed at select monitoring wells to evaluate the hydraulic conductivity of saturated material at the Site and support design of the proposed extraction system. The following activities will be performed as part of the aquifer tests:

- Short-duration pumping tests will be attempted at eight monitoring wells.

- In the event that some monitoring wells demonstrate relatively low yields and cannot sustain pumping without going dry, slug tests will be performed at those monitoring wells demonstrating relatively low yield.

- Long-term pumping tests will be completed at one well after short-term pumping tests are completed and data from those tests have been evaluated.

2.2.1 Short-Duration Pumping Tests

In general, short-duration pumping tests involve pumping the well at a constant rate for approximately 60 to 90 minutes and measuring water levels before, during, and after the test. Under ideal conditions, a drawdown target of approximately 90 percent or less of the pre-pumping water column should be maintained. It is important to measure the pumping rate, duration, and total volume of water removed as accurately as possible, in addition to the other measurements required in the Standard Operating Procedure (SOP) (Appendix C).

Short-duration pumping tests will be attempted at eight monitoring wells at the Site. Pumping tests will be attempted at the wells using submersible pumps (capable of rates from approximately 0.5 to 4 gallons per minute (gpm)) and/or peristaltic pumps (capable of rates from approximately 0.1 to 0.25 gpm). The list of wells proposed for testing includes: MW-149R, MW-8R, MW-104, MW-518, MW-510, LM-2, MW-129R and MW-500 (Figure 3). These wells were selected to represent the variety of fill and native materials at the Site. Also, these wells are located in areas where future installation of extraction wells may be considered and will provide representative hydraulic parameter data for those areas. In the event that some monitoring wells demonstrate relatively low yields and cannot sustain pumping without going dry, slug tests will be performed at those monitoring wells demonstrating relatively low yield.

Water levels will be recorded with a downhole data-logging pressure transducer (Level Troll® 700) along with a transducer with the capabilities to record salinity (Aqua Troll® 200). Time-drawdown data will be analyzed using AQTESOLV® (Duffield, 2007). Transducers will remain deployed at staff gauges utilized during the tidal study locations D1, D2, D3, D4, D5, and D6 (Figure 3) and will be read once during the day at those locations.

The general guidelines for performing short-duration pumping tests are as follows:

- After the tidal study, the Aqua Troll 200 transducers will remain deployed in wells LM-2, MW-8R, MW-104, MW-122, MW-129R, MW-149R, MW-500, MW-502, MW-510, MW-515, and MW-518 collecting data at a rate of every 10 minutes. The Aqua Troll 200 transducers will be removed from the wells immediately preceding initiation of the short-term pumping tests.

- A day or two before initiating the short-duration pumping tests, determine approximate yield of well by conducting a short step-drawdown test (approximately 10 to 20 minutes). The purpose of the short step-drawdown test is to determine if the well can be pumped at a constant rate while maintaining a steady-state drawdown. Also, this will establish a target pumping rate for the actual short-duration pumping test. If the well can be pumped at a constant rate while maintaining a steady-state drawdown (or no measurable drawdown), conduct a short-duration pumping test per the methods outlined below. If a steady-state drawdown cannot be maintained at a constant pumping rate, even if the pump is set at the minimum pumping rate (i.e., the well pumps dry), then conduct a slug test outlined below in Section 2.2.2.

- Measure initial (static) water level and total well depth. Calculate the volume of water in the well based on diameter, total depth, and water level.

- Set the Level Troll 700 pressure transducer to record water levels at a frequency of one measurement every second or less. Install the Level Troll 700 and the Aqua Troll 200 in the well.

- Insert downhole tubing into the well so the intake is just below the pressure transducer (approximately 1 foot). Allow water level to equilibrate.

- Begin pumping the well at the selected pumping rate appropriate for the well while monitoring water levels with the pressure transducer and manual water level indicator (for verification purposes). Take measurements with manual water level indicator every five minutes and record the measurements in the field notebook or field form.

- If the well pumps dry, or is about to pump dry at the minimum pumping rate using a submersible pump, then terminate the test and attempt the test with a peristaltic pump and if that also dries the well, perform a slug test as outlined below in Section 3.2.2.

- If the well does not pump dry at the minimum pumping rate, continue pumping at a constant minimum rate, verify the pumping rate every five minutes, and continue pumping in accordance with the short-duration pumping test procedures outlined here and in the SOP (Appendix C). It is important to continuously document the pumping rate, time elapsed, and total amount of groundwater removed (after the test) as accurately as possible. This can be accomplished with a calibrated bucket or other container and stopwatch.

- Measure water levels with the pressure transducer and manual water level indicator. If measuring water levels with a pressure transducer, be sure the transducer data are stored in an appropriate location (i.e., a laptop computer) for future retrieval. Check that the time indicated on the pressure transducer is synchronized with the site location and stopwatch(es).

- The test may be terminated after 30 minutes if drawdown has stabilized at 90 percent or less of the static water level at a constant pumping rate for a minimum of 15 minutes. Be sure that at least a full well volume of water plus the approximately sandpack volume has been removed prior to terminating the test.

- If stabilized drawdown cannot be maintained at the selected constant pumping rate for any reason, then terminate the test, allow water level to re-equilibrate, and perform the test again at a lower constant pumping rate or complete a slug test if the well cannot be tested with a pumping test.

- At the end of the test, continue to record recovery of water levels with the pressure transducer. The test is considered complete if the water levels recover to within 90 percent or more of the static water level. If the well is recharging slowly, after 30 minutes, continue monitoring with a water level meter approximately every hour. Leave the transducer in the well and use the backup transducer and pump. If well is still recovering overnight, remove pump and transducer and make note of the time equipment was removed.

- If stabilized drawdown cannot be maintained at the lowest pumping rate possible with the selected pump, then perform a slug test in accordance with the procedures outlined below.

2.2.2 Slug Tests

Slug tests will be performed in accordance with the SOP provided in Appendix D. In general, slug tests involve removing a slug of water from the well as rapidly as possible so as to create a nearly instantaneous change in the hydraulic head in the well, then recording the rate of water level recovery in the well. The slug of water may be removed by manual bailing, pumping the well at the maximum pumping rate, or removing a slug of known volume that was placed into the well prior to testing. Sufficient pre-test water level monitoring should be performed to establish the pre-pumping water level. Water levels should be recorded with a downhole data-logging pressure transducer. Occasional measurements with a manual water level indicator should also be recorded.

The general guidelines for performing slug tests are as follows:

- Measure static water level and total well depth.

- Install downhole data-logging pressure transducer one foot above the bottom of the well. Measure the length of time the transducer is deployed in the well. Connect the transducer to a laptop computer. Configure transducer connection to monitor water levels in real time.

- Set the pressure transducer to record water levels at a high frequency (for example, one measurement every second).

- Begin logging water level with pressure transducer.

- Quickly remove a slug of water from the well using the selected water withdrawal method, in accordance with the SOP. In this case it is likely the well will be pumped to dry or nearly dry conditions in the shortest amount of time possible with a high flow downhole pump. It is critical to calculate the total volume of water removed as accurately as possible to manage the purged water appropriately. For a well at a diameter of two inches, there is approximately 0.163 gallon of water per foot of water column. For a well at a diameter of four inches, there is approximately 0.65 gallon of water per foot of water column. If removing the slug of water with a pump, collect the discharge water into buckets or other type of container that will allow accurate measurement of water volume. Use a similar strategy if manually bailing the slug of water out of the well; collect the bailed water into a five-gallon bucket.

- After the slug of water has been removed from the well, collect water level recovery data at as high a frequency as possible using the pressure transducer and periodic measurements with a manual water level indicator if possible (approximately every one to two minutes at start of recovery and then every five minutes).

- Allow the water levels to return to within 90 percent or greater of the static water level. If the well is recharging slowly, after 30 minutes, continue monitoring with a water level meter approximately every hour. Leave the transducer and pump in the well and use the backup transducer and pump. If the well is still recovering overnight, remove pump and transducer and make note of the time equipment was removed.

- Check the water level data to see that a good, quality data set has been collected. The data should show an initial, nearly instantaneous decrease in water level immediately after the slug has been removed, and a smooth water-level recovery curve.

- The test may be terminated if a good, quality data set has been collected and the water levels have returned to within 90 percent or greater of the static water level.

Some geologic formations of very low permeability such as tight clays will not recharge the well rapidly and it may take days, weeks, or possibly even months for water levels to return to within 90 percent or greater of the static water level. In the case of delayed water level recovery, perform the slug test in accordance with these guidelines and the SOP, and collect as much water level recovery data as possible within the constraints of the project scope, budget, and schedule. If the field work extends over several days, it may be acceptable to return to a very slowly-recharging monitoring well once or twice a day to measure water levels until the field phase has ended.

Downhole and re-useable equipment will be decontaminated prior to use at each location. Purge and decontamination water will be contained on-site in a drum and disposed of offsite.

2.2.3 Long-Term Pumping Test

A long-term pumping test will be completed after the short-duration single-well pumping tests. The objective of the long-term pumping test is to confirm interpretations made during the short-term pumping test, obtain estimates of storage parameters, and evaluate responses in other wells to long-term pumping. After the short-term pumping tests, the data will be evaluated to select one pumping well and appropriate monitoring wells (for use as observation wells) for a long-term pumping test (approximately 24 hours). The long-term pumping test will be performed in accordance with the attached SOP (Appendix E).

In general, this test involves pumping a well at a constant rate and measuring water levels before, during, and after the test at the pumping well and select nearby monitoring wells. It is important to measure the pumping rate, duration, and total volume of water removed as accurately as possible, in addition to the other measurements required in the SOP. Water levels will be recorded at the pumping well with a Level Troll 700 downhole data-logging pressure transducer. Water levels at observation wells can be recorded with data-logging pressure transducers and a manual water level indicator. An Aqua Troll® 200 will also be deployed in the pumping well to record any potential changes in salinity during the longer duration test. Pressure transducers will remain deployed at staff gauges utilized during the tidal study locations D1, D2, D3, D4, D5, and D6 (Figure 3) and will be read once during the 24-hour testing period at those locations.

Time-drawdown data will be analyzed using AQTESOLV® (Duffield, 2007) for transmissivity and storage parameters.

Downhole and re-useable equipment will be decontaminated prior to use at each location. Purge and decontamination water will be contained on-site in a drum and disposed of offsite.

Water generated during pumping tests will be stored onsite in a 2,000 gallon trailer mounted polyethylene tank. The tank will be emptied via vacuum truck and its contents will be taken to an approved waste recycling facility by Emerald Services of Seattle, Washington.

3. Deliverables

A technical memorandum will be submitted summarizing the results of the tidal study and aquifer testing. The information contained in the memorandum will include a summary of tidal efficiency factors for each well location (likely an average from the study) and a graphical presentation of tidal fluctuations measured at each well, staff gauge and the Puget Sound. Also, a summary of hydraulic conductivity values and graphs presenting the time-drawdown curves and analysis will be included.

4. References

Agreed Order No. DE 4460 State of Washington Department of Ecology, June 2007.

ARCADIS. *Phase I Remedial Implementation As-Built Report, Unocal Edmonds Bulk Fuel Terminal Lower Yard*. July 31, 2009 (ARCADIS 2009)

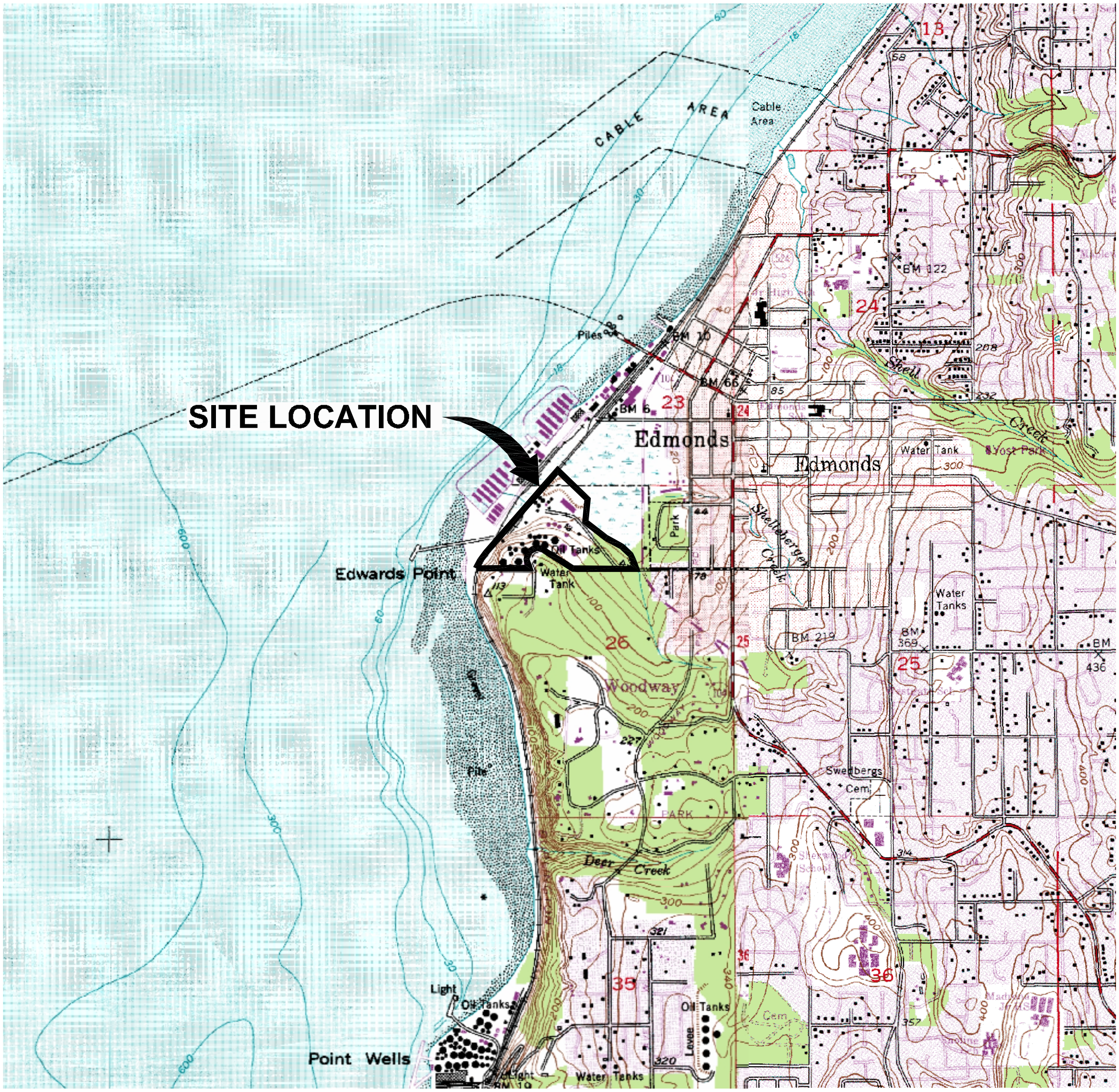
ARCADIS. *FINAL – Phase II Remedial Implementation As-Built Report, Unocal Edmonds Bulk Fuel Terminal Lower Yard*. January 18, 2010 (ARCADIS 2010).

Duffield, G. 2007. AQTESOLV® Professional Version 4.5. Hydrosolve, Inc.

Maul Foster and Alongi. Lower Yard Interim Action As-built Report , *Unocal Edmonds Terminal– Volume 1. November 30, 2002* (MFA 2002).

Maul Foster and Alongi. 2003 Lower Yard Interim Action As-Built Report, Detention Basin No. 1, Southwest Lower Yard, Metals Area 3, and Storm Drain Line Excavations – Volume 1. February 26, 2004 (MFA 2004)

Figures



REFERENCE: USGS QUADS., 7.5 MIN. SERIES (TOPOGRAPHIC) - EDMONDS EAST, WASH. AND EDMONDS WEST, WASH.

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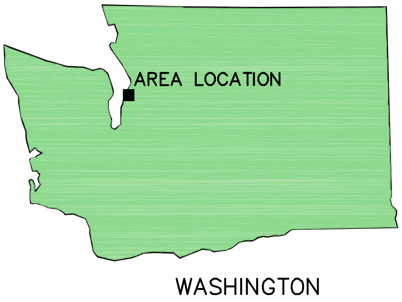

CHEVRON ENVIRONMENTAL MANAGEMENT COMPANY
FORMER UNOCAL TERMINAL
EDMONDS, WASHINGTON

SITE LOCATION MAP

ARCADIS

FIGURE
1

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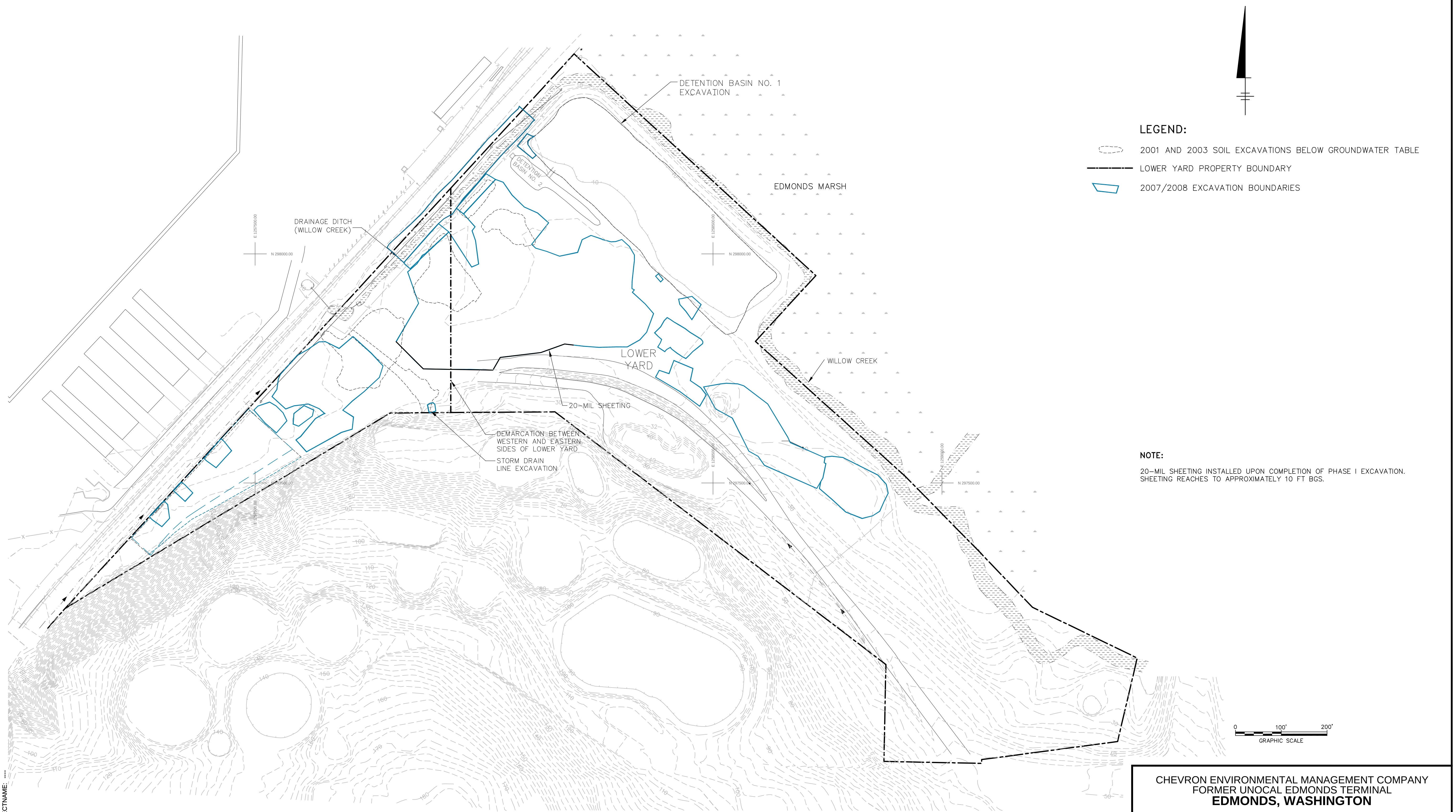

LEGEND:

- 2001 AND 2003 SOIL EXCAVATIONS BELOW GROUNDWATER TABLE
- LOWER YARD PROPERTY BOUNDARY
- 2007/2008 EXCAVATION BOUNDARIES

NOTE:

20-MIL SHEETING INSTALLED UPON COMPLETION OF PHASE I EXCAVATION. SHEETING REACHES TO APPROXIMATELY 10 FT BGS.

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EDMONDS, WASHINGTON

SITE LAYOUT MAP

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FIGURE
2

CITY: (TAMPA, FL) SYRACUSE, NY GROUP: ENVCAD DB: (J. RICHARDS), K. DAVIS, P. LISTER PM: R. ANDRESEN TM: S. ZORN TR: D. RASAR LYR: ON=*;OFF=*REF*
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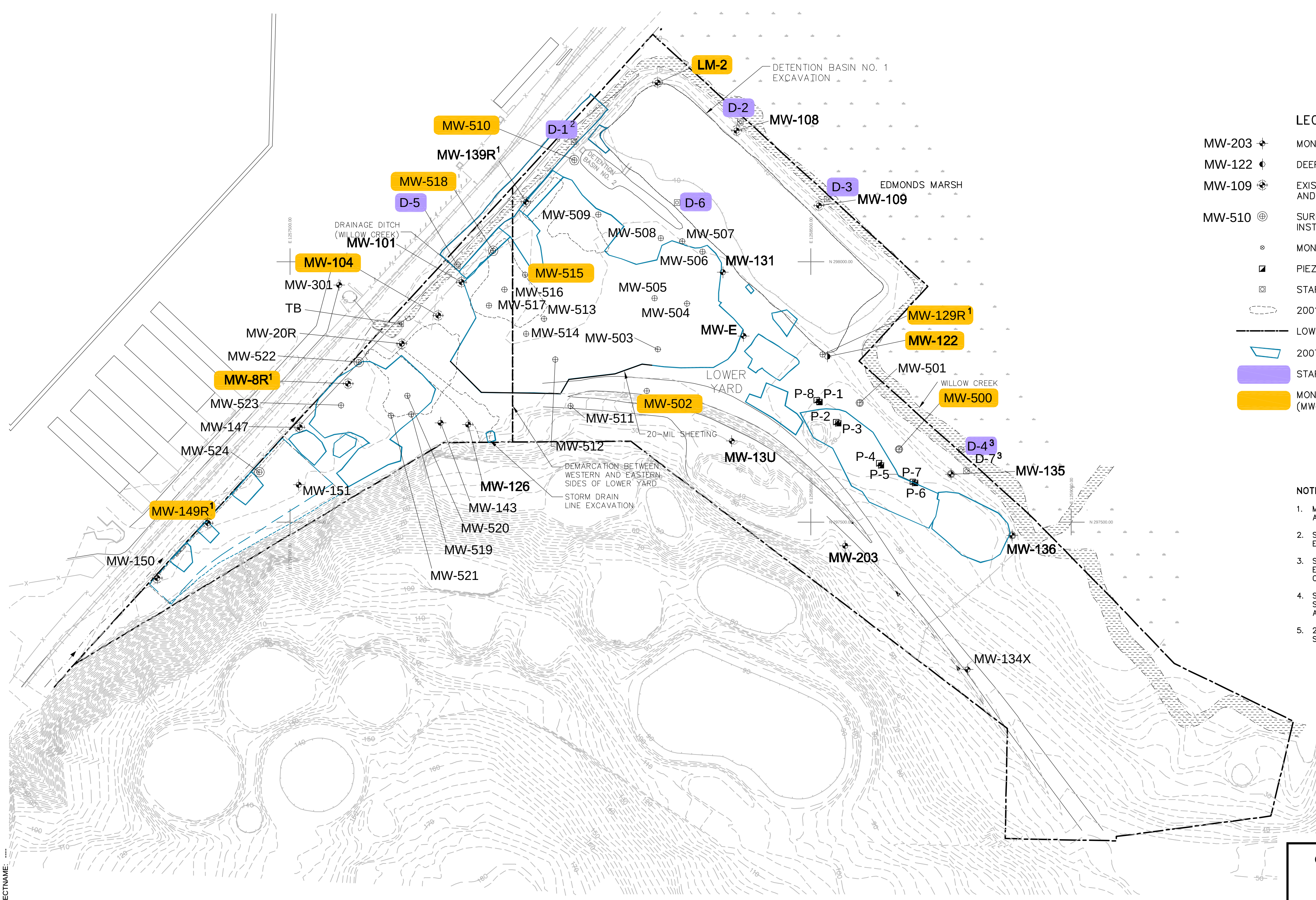

0 100' 200'
GRAPHIC SCALE

LEGEND:

MW-203 ✦	MONITORING WELL LOCATION AND DESIGNATION
MW-122 ◐	DEEP MONITORING WELL LOCATION AND DESIGNATION
MW-109 ✦	EXISTING SURFACE WATER COMPLIANCE MONITORING WELL LOCATION AND DESIGNATION
MW-510 ⊕	SURFACE WATER COMPLIANCE MONITORING WELL LOCATION INSTALLED OCTOBER 2008
⊗	MONITORING WELL LOCATION INSTALLED OCTOBER 2008
◪	PIEZOMETER
⊡	STAFF GAUGE
⬭	2001 AND 2003 SOIL EXCAVATIONS BELOW GROUNDWATER TABLE
—·—·—	LOWER YARD PROPERTY BOUNDARY
▱	2007/2008 EXCAVATION BOUNDARIES
🟪	STAFF GAUGE FOR PROPOSED HYDRAULIC EVALUATION
🟨	MONITORING WELL FOR PROPOSED HYDRAULIC EVALUATION (MW-122 PROPOSED FOR TIDAL STUDY ONLY)

NOTES:

1. MONITORING WELLS MW-129R, MW-139R, MW-8R, AND MW-149R WERE ABANDONED DURING INTERIM ACTION AND REPLACED IN OCTOBER 2008.
2. STAFF GAUGE D-1 RE-ESTABLISHED PRIOR TO JUNE 2009 SAMPLING EVENT.
3. STAFF GAUGE D-4 WAS ESTABLISHED PRIOR TO JUNE 2009 SAMPLING EVENT TO REPLACE STAFF GAUGE D-7 WHICH IS NOT WITHIN THE WILLOW CREEK CHANNEL.
4. STAFF GAUGES WERE RESURVEYED BY OTAK INCORPORATED JUNE 1, 2009. STAFF GAUGES WERE SURVEYED FROM TOP OF GAUGE AND WATER LEVELS ARE NOW MEASURED FROM TOP DOWN TO WATER.
5. 20-MIL SHEETING INSTALLED UPON COMPLETION OF PHASE I EXCAVATION. SHEETING REACHES TO APPROXIMATELY 10 FT BGS.

CHEVRON ENVIRONMENTAL MANAGEMENT COMPANY
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EDMONDS, WASHINGTON

MONITORING WELL LOCATIONS

ARCADIS

FIGURE
3

CITY: (TAMPA, FL) SYRACUSE, NY GROUP: ENVCAD DB: (J. RICHARDS), K. DAVIS, P. LISTER PM: R. ANDRESEN TM: S. ZORN TR: D. RASAR LYR: ON=*;OFF=*REF*
G:\ENVCAD\SYRACUSE\ACT\B0045362\0002\00002\DWG\45362B05.dwg LAYOUT: 3 SAVED: 10/25/2010 1:39 PM ACADVER: 18.0S (LMS TECH) PAGESETUP: ---- PLOTSTYLETABLE: PLTFULL.CTB PLOTTED: 10/25/2010 1:39 PM BY: JONES, WENDY
XREFS: 45362X01 45362X02 45362X00 IMAGES: PROJECTNAME: ----

Appendix **A**

Edmonds, Washington Tide Tables

TIDES & CURRENTS

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2011 NOAA Tide Predictions: Edmonds

(Reference station: Seattle, Corrections Applied: Times: High +0 hr. 0 min., Low -0 hr. 4 min., Heights: High *0.96, Low *0.99)

January - Edmonds

Date	Day	Time	Height	Time	Height	Time	Height	Time	Height	Time	Height
01/01/2011	Sat	03:53AM LST	10.8 H	08:32AM LST	7.9 L	01:26PM LST	11.0 H	08:42PM LST	-1.7 L		
01/02/2011	Sun	04:41AM LST	11.4 H	09:36AM LST	7.8 L	02:17PM LST	10.8 H	09:25PM LST	-2.0 L		
01/03/2011	Mon	05:21AM LST	11.7 H	10:29AM LST	7.5 L	03:06PM LST	10.6 H	10:07PM LST	-1.9 L		
01/04/2011	Tue	05:56AM LST	11.9 H	11:14AM LST	7.2 L	03:52PM LST	10.3 H	10:46PM LST	-1.7 L		
01/05/2011	Wed	06:25AM LST	11.9 H	11:55AM LST	6.8 L	04:38PM LST	9.9 H	11:24PM LST	-1.2 L		
01/06/2011	Thu	06:52AM LST	11.9 H	12:35PM LST	6.3 L	05:24PM LST	9.5 H				
01/07/2011	Fri	12:01AM LST	-0.5 L	07:18AM LST	11.8 H	01:14PM LST	5.8 L	06:12PM LST	9.0 H		
01/08/2011	Sat	12:38AM LST	0.4 L	07:45AM LST	11.8 H	01:54PM LST	5.2 L	07:03PM LST	8.5 H		
01/09/2011	Sun	01:14AM LST	1.5 L	08:14AM LST	11.7 H	02:37PM LST	4.6 L	07:59PM LST	8.1 H		
01/10/2011	Mon	01:51AM LST	2.8 L	08:45AM LST	11.5 H	03:22PM LST	3.9 L	09:04PM LST	7.7 H		
01/11/2011	Tue	02:30AM LST	4.2 L	09:18AM LST	11.2 H	04:10PM LST	3.2 L	10:22PM LST	7.5 H		
01/12/2011	Wed	03:13AM LST	5.6 L	09:54AM LST	10.9 H	05:01PM LST	2.5 L				
01/13/2011	Thu	12:05AM LST	7.8 H	04:10AM LST	7.0 L	10:34AM LST	10.7 H	05:53PM LST	1.7 L		
01/14/2011	Fri	02:04AM LST	8.4 H	05:32AM LST	8.0 L	11:19AM LST	10.4 H	06:44PM LST	0.9 L		
01/15/2011	Sat	03:15AM LST	9.4 H	07:08AM LST	8.5 L	12:08PM LST	10.3 H	07:32PM LST	0.0 L		
01/16/2011	Sun	03:57AM LST	10.2 H	08:22AM LST	8.6 L	12:59PM LST	10.3 H	08:18PM LST	-0.9 L		
01/17/2011	Mon	04:29AM LST	10.8 H	09:13AM LST	8.4 L	01:50PM LST	10.5 H	09:02PM LST	-1.7 L		
01/18/2011	Tue	04:57AM LST	11.2 H	09:55AM LST	7.9 L	02:40PM LST	10.7 H	09:45PM LST	-2.2 L		
01/19/2011	Wed	05:24AM LST	11.6 H	10:36AM LST	7.3 L	03:31PM LST	10.8 H	10:28PM LST	-2.4 L		
01/20/2011	Thu	05:52AM LST	12.0 H	11:17AM LST	6.5 L	04:23PM LST	10.8 H	11:11PM LST	-2.2 L		
01/21/2011	Fri	06:22AM LST	12.3 H	12:02PM LST	5.5 L	05:17PM LST	10.7 H	11:54PM LST	-1.5 L		
01/22/2011	Sat	06:54AM LST	12.5 H	12:49PM LST	4.5 L	06:15PM LST	10.3 H				
01/23/2011	Sun	12:37AM LST	-0.3 L	07:28AM LST	12.7 H	01:39PM LST	3.4 L	07:18PM LST	9.7 H		
01/24/2011	Mon	01:22AM LST	1.3 L	08:05AM LST	12.6 H	02:31PM LST	2.4 L	08:27PM LST	9.1 H		
01/25/2011	Tue	02:09AM LST	3.1 L	08:43AM LST	12.4 H	03:28PM LST	1.5 L	09:48PM LST	8.7 H		
01/26/2011	Wed	03:02AM LST	5.0 L	09:26AM LST	12.0 H	04:28PM LST	0.9 L	11:31PM LST	8.6 H		
01/27/2011	Thu	04:09AM LST	6.6 L	10:15AM LST	11.4 H	05:32PM LST	0.3 L				
01/28/2011	Fri	01:27AM LST	9.2 H	05:40AM LST	7.7 L	11:12AM LST	10.9 H	06:36PM LST	-0.1 L		
01/29/2011	Sat	02:51AM LST	10.1 H	07:26AM LST	8.0 L	12:15PM LST	10.5 H	07:35PM LST	-0.5 L		
01/30/2011	Sun	03:46AM LST	10.8 H	08:45AM LST	7.7 L	01:18PM LST	10.2 H	08:27PM LST	-0.8 L		
01/31/2011	Mon	04:28AM LST	11.2 H	09:40AM LST	7.2 L	02:16PM LST	10.1 H	09:13PM LST	-0.9 L		

All times are listed in Local Standard Time(LST) or, Local Daylight Time (LDT) (when applicable). All heights are in feet referenced to Mean Lower Low Water (MLLW).

February - Edmonds

Date	Day	Time	Height	Time	Height	Time	Height	Time	Height	Time	Height
02/01/2011	Tue	05:02AM LST	11.4 H	10:23AM LST	6.7 L	03:08PM LST	10.0 H	09:53PM LST	-0.8 L		
02/02/2011	Wed	05:29AM LST	11.5 H	10:59AM LST	6.1 L	03:54PM LST	9.9 H	10:31PM LST	-0.5 L		
02/03/2011	Thu	05:51AM LST	11.5 H	11:31AM LST	5.6 L	04:38PM LST	9.7 H	11:06PM LST	0.0 L		
02/04/2011	Fri	06:10AM LST	11.5 H	12:02PM LST	5.0 L	05:21PM LST	9.6 H	11:39PM LST	0.7 L		
02/05/2011	Sat	06:31AM LST	11.5 H	12:33PM LST	4.4 L	06:04PM LST	9.3 H				
02/06/2011	Sun	12:13AM LST	1.6 L	06:54AM LST	11.5 H	01:06PM LST	3.7 L	06:51PM LST	9.1 H		
02/07/2011	Mon	12:47AM LST	2.6 L	07:21AM LST	11.4 H	01:42PM LST	3.1 L	07:40PM LST	8.8 H		
02/08/2011	Tue	01:21AM LST	3.8 L	07:50AM LST	11.2 H	02:22PM LST	2.6 L	08:36PM LST	8.5 H		
02/09/2011	Wed	01:58AM LST	5.0 L	08:21AM LST	10.8 H	03:06PM LST	2.1 L	09:41PM LST	8.4 H		
02/10/2011	Thu	02:39AM LST	6.2 L	08:55AM LST	10.5 H	03:56PM LST	1.8 L	11:05PM LST	8.4 H		
02/11/2011	Fri	03:31AM LST	7.4 L	09:36AM LST	10.1 H	04:52PM LST	1.4 L				
02/12/2011	Sat	01:04AM LST	8.6 H	04:54AM LST	8.2 L	10:26AM LST	9.8 H	05:53PM LST	0.8 L		
02/13/2011	Sun	02:33AM LST	9.3 H	06:41AM LST	8.5 L	11:29AM LST	9.7 H	06:52PM LST	0.2 L		
02/14/2011	Mon	03:17AM LST	10.0 H	07:59AM LST	8.2 L	12:35PM LST	9.8 H	07:47PM LST	-0.5 L		
02/15/2011	Tue	03:47AM LST	10.6 H	08:49AM LST	7.6 L	01:36PM LST	10.1 H	08:37PM LST	-1.1 L		
02/16/2011	Wed	04:13AM LST	10.9 H	09:30AM LST	6.7 L	02:34PM LST	10.5 H	09:23PM LST	-1.4 L		
02/17/2011	Thu	04:39AM LST	11.4 H	10:10AM LST	5.6 L	03:30PM LST	10.8 H	10:08PM LST	-1.3 L		
02/18/2011	Fri	05:07AM LST	11.8 H	10:51AM LST	4.4 L	04:25PM LST	10.9 H	10:52PM LST	-0.8 L		
02/19/2011	Sat	05:36AM LST	12.1 H	11:34AM LST	3.1 L	05:21PM LST	10.9 H	11:35PM LST	0.2 L		
02/20/2011	Sun	06:09AM LST	12.4 H	12:19PM LST	1.9 L	06:19PM LST	10.8 H				
02/21/2011	Mon	12:20AM LST	1.5 L	06:43AM LST	12.4 H	01:07PM LST	0.9 L	07:20PM LST	10.4 H		
02/22/2011	Tue	01:06AM LST	3.1 L	07:21AM LST	12.2 H	01:57PM LST	0.3 L	08:27PM LST	9.9 H		
02/23/2011	Wed	01:56AM LST	4.7 L	08:01AM LST	11.7 H	02:50PM LST	0.0 L	09:44PM LST	9.5 H		
02/24/2011	Thu	02:53AM LST	6.1 L	08:48AM LST	11.1 H	03:49PM LST	0.1 L	11:21PM LST	9.4 H		
02/25/2011	Fri	04:10AM LST	7.2 L	09:43AM LST	10.4 H	04:55PM LST	0.3 L				
02/26/2011	Sat	01:07AM LST	9.7 H	05:58AM LST	7.6 L	10:51AM LST	9.7 H	06:04PM LST	0.4 L		
02/27/2011	Sun	02:23AM LST	10.2 H	07:39AM LST	7.3 L	12:08PM LST	9.3 H	07:11PM LST	0.4 L		
02/28/2011	Mon	03:15AM LST	10.6 H	08:43AM LST	6.6 L	01:21PM LST	9.2 H	08:08PM LST	0.4 L		

All times are listed in Local Standard Time(LST) or, Local Daylight Time (LDT) (when applicable). All heights are in feet referenced to Mean Lower Low Water (MLLW).

March - Edmonds

Date	Day	Time	Height	Time	Height	Time	Height	Time	Height	Time	Height
03/01/2011	Tue	03:53AM LST	10.8 H	09:28AM LST	5.8 L	02:24PM LST	9.3 H	08:55PM LST	0.5 L		
03/02/2011	Wed	04:22AM LST	10.8 H	10:04AM LST	5.1 L	03:15PM LST	9.4 H	09:36PM LST	0.7 L		
03/03/2011	Thu	04:43AM LST	10.8 H	10:33AM LST	4.5 L	04:00PM LST	9.5 H	10:12PM LST	1.1 L		
03/04/2011	Fri	05:00AM LST	10.8 H	10:59AM LST	3.8 L	04:40PM LST	9.6 H	10:45PM LST	1.7 L		
03/05/2011	Sat	05:17AM LST	10.8 H	11:25AM LST	3.1 L	05:20PM LST	9.7 H	11:18PM LST	2.4 L		
03/06/2011	Sun	05:38AM LST	10.9 H	11:52AM LST	2.4 L	06:01PM LST	9.7 H	11:51PM LST	3.3 L		
03/07/2011	Mon	06:02AM LST	10.8 H	12:23PM LST	1.8 L	06:43PM LST	9.7 H				
03/08/2011	Tue	12:25AM LST	4.1 L	06:29AM LST	10.8 H	12:57PM LST	1.3 L	07:27PM LST	9.6 H		
03/09/2011	Wed	01:01AM LST	5.0 L	06:58AM LST	10.5 H	01:34PM LST	1.0 L	08:17PM LST	9.5 H		
03/10/2011	Thu	01:40AM LST	5.9 L	07:29AM LST	10.2 H	02:17PM LST	0.8 L	09:14PM LST	9.2 H		
03/11/2011	Fri	02:24AM LST	6.8 L	08:03AM LST	9.8 H	03:06PM LST	0.7 L	10:24PM LST	9.0 H		
03/12/2011	Sat	03:21AM LST	7.5 L	08:45AM LST	9.4 H	04:03PM LST	0.7 L	11:51PM LST	9.1 H		
03/13/2011	Sun	05:45AM LDT	7.9 L	10:46AM LDT	9.0 H	06:06PM LDT	0.6 L				
03/14/2011	Mon	02:15AM LDT	9.4 H	07:23AM LDT	7.7 L	12:03PM LDT	8.9 H	07:12PM LDT	0.4 L		
03/15/2011	Tue	03:08AM LDT	9.9 H	08:33AM LDT	7.0 L	01:20PM LDT	9.1 H	08:13PM LDT	0.1 L		
03/16/2011	Wed	03:44AM LDT	10.4 H	09:21AM LDT	5.9 L	02:30PM LDT	9.5 H	09:08PM LDT	0.0 L		
03/17/2011	Thu	04:14AM LDT	10.8 H	10:02AM LDT	4.7 L	03:33PM LDT	10.1 H	09:58PM LDT	0.1 L		
03/18/2011	Fri	04:44AM LDT	11.2 H	10:43AM LDT	3.2 L	04:32PM LDT	10.6 H	10:45PM LDT	0.6 L		
03/19/2011	Sat	05:14AM LDT	11.6 H	11:24AM LDT	1.7 L	05:29PM LDT	10.9 H	11:31PM LDT	1.4 L		
03/20/2011	Sun	05:46AM LDT	11.8 H	12:06PM LDT	0.3 L	06:26PM LDT	11.1 H				
03/21/2011	Mon	12:18AM LDT	2.5 L	06:21AM LDT	11.9 H	12:50PM LDT	-0.7 L	07:23PM LDT	11.1 H		
03/22/2011	Tue	01:05AM LDT	3.7 L	06:58AM LDT	11.8 H	01:36PM LDT	-1.3 L	08:22PM LDT	10.9 H		
03/23/2011	Wed	01:55AM LDT	4.9 L	07:39AM LDT	11.4 H	02:24PM LDT	-1.4 L	09:25PM LDT	10.7 H		
03/24/2011	Thu	02:50AM LDT	5.8 L	08:24AM LDT	10.8 H	03:16PM LDT	-1.0 L	10:35PM LDT	10.3 H		
03/25/2011	Fri	03:56AM LDT	6.6 L	09:15AM LDT	10.0 H	04:13PM LDT	-0.4 L	11:57PM LDT	10.0 H		
03/26/2011	Sat	05:23AM LDT	7.0 L	10:19AM LDT	9.1 H	05:16PM LDT	0.4 L				
03/27/2011	Sun	01:23AM LDT	10.0 H	07:10AM LDT	6.8 L	11:37AM LDT	8.4 H	06:26PM LDT	1.0 L		
03/28/2011	Mon	02:31AM LDT	10.1 H	08:29AM LDT	6.0 L	01:04PM LDT	8.2 H	07:36PM LDT	1.5 L		
03/29/2011	Tue	03:20AM LDT	10.3 H	09:22AM LDT	5.0 L	02:23PM LDT	8.3 H	08:37PM LDT	1.8 L		
03/30/2011	Wed	03:56AM LDT	10.4 H	10:02AM LDT	4.3 L	03:28PM LDT	8.6 H	09:28PM LDT	2.1 L		
03/31/2011	Thu	04:22AM LDT	10.4 H	10:33AM LDT	3.4 L	04:20PM LDT	8.9 H	10:11PM LDT	2.6 L		

All times are listed in Local Standard Time(LST) or, Local Daylight Time (LDT) (when applicable). All heights are in feet referenced to Mean Lower Low Water (MLLW).

April - Edmonds

Date	Day	Time	Height	Time	Height	Time	Height	Time	Height	Time	Height
04/01/2011	Fri	04:41AM LDT	10.4 H	10:59AM LDT	2.6 L	05:05PM LDT	9.3 H	10:49PM LDT	3.1 L		
04/02/2011	Sat	05:00AM LDT	10.4 H	11:22AM LDT	1.9 L	05:45PM LDT	9.6 H	11:24PM LDT	3.7 L		
04/03/2011	Sun	05:20AM LDT	10.4 H	11:47AM LDT	1.1 L	06:22PM LDT	9.9 H	11:58PM LDT	4.4 L		
04/04/2011	Mon	05:44AM LDT	10.3 H	12:14PM LDT	0.5 L	07:00PM LDT	10.1 H				
04/05/2011	Tue	12:33AM LDT	5.0 L	06:10AM LDT	10.2 H	12:45PM LDT	0.0 L	07:39PM LDT	10.3 H		
04/06/2011	Wed	01:10AM LDT	5.6 L	06:39AM LDT	10.1 H	01:20PM LDT	-0.4 L	08:20PM LDT	10.3 H		
04/07/2011	Thu	01:49AM LDT	6.1 L	07:09AM LDT	9.8 H	01:58PM LDT	-0.5 L	09:06PM LDT	10.2 H		
04/08/2011	Fri	02:32AM LDT	6.6 L	07:42AM LDT	9.5 H	02:41PM LDT	-0.5 L	09:58PM LDT	10.1 H		
04/09/2011	Sat	03:22AM LDT	7.1 L	08:21AM LDT	9.1 H	03:30PM LDT	-0.3 L	10:57PM LDT	9.9 H		
04/10/2011	Sun	04:24AM LDT	7.3 L	09:12AM LDT	8.7 H	04:24PM LDT	0.0 L				
04/11/2011	Mon	12:03AM LDT	9.8 H	05:44AM LDT	7.1 L	10:23AM LDT	8.4 H	05:26PM LDT	0.4 L		
04/12/2011	Tue	01:05AM LDT	9.9 H	07:04AM LDT	6.5 L	11:49AM LDT	8.2 H	06:31PM LDT	0.8 L		
04/13/2011	Wed	01:56AM LDT	10.2 H	08:05AM LDT	5.3 L	01:13PM LDT	8.4 H	07:35PM LDT	1.2 L		
04/14/2011	Thu	02:37AM LDT	10.6 H	08:52AM LDT	3.9 L	02:29PM LDT	8.8 H	08:35PM LDT	1.7 L		
04/15/2011	Fri	03:13AM LDT	10.9 H	09:35AM LDT	2.3 L	03:37PM LDT	9.6 H	09:30PM LDT	2.3 L		
04/16/2011	Sat	03:47AM LDT	11.2 H	10:16AM LDT	0.6 L	04:39PM LDT	10.3 H	10:22PM LDT	3.1 L		
04/17/2011	Sun	04:22AM LDT	11.5 H	10:58AM LDT	-0.9 L	05:37PM LDT	10.9 H	11:13PM LDT	3.9 L		
04/18/2011	Mon	04:58AM LDT	11.6 H	11:40AM LDT	-2.0 L	06:32PM LDT	11.3 H				
04/19/2011	Tue	12:03AM LDT	4.8 L	05:37AM LDT	11.4 H	12:24PM LDT	-2.6 L	07:27PM LDT	11.5 H		
04/20/2011	Wed	12:55AM LDT	5.4 L	06:18AM LDT	11.1 H	01:09PM LDT	-2.7 L	08:23PM LDT	11.4 H		
04/21/2011	Thu	01:50AM LDT	6.0 L	07:03AM LDT	10.6 H	01:56PM LDT	-2.3 L	09:20PM LDT	11.2 H		
04/22/2011	Fri	02:50AM LDT	6.4 L	07:53AM LDT	9.8 H	02:46PM LDT	-1.5 L	10:20PM LDT	10.8 H		
04/23/2011	Sat	04:00AM LDT	6.6 L	08:49AM LDT	8.9 H	03:39PM LDT	-0.5 L	11:23PM LDT	10.6 H		
04/24/2011	Sun	05:26AM LDT	6.3 L	09:58AM LDT	8.2 H	04:36PM LDT	0.5 L				
04/25/2011	Mon	12:25AM LDT	10.4 H	06:53AM LDT	5.7 L	11:19AM LDT	7.5 H	05:40PM LDT	1.6 L		
04/26/2011	Tue	01:21AM LDT	10.2 H	07:59AM LDT	4.8 L	12:50PM LDT	7.3 H	06:47PM LDT	2.5 L		
04/27/2011	Wed	02:06AM LDT	10.2 H	08:47AM LDT	3.8 L	02:16PM LDT	7.6 H	07:52PM LDT	3.3 L		
04/28/2011	Thu	02:41AM LDT	10.2 H	09:24AM LDT	2.8 L	03:27PM LDT	8.1 H	08:49PM LDT	3.9 L		
04/29/2011	Fri	03:09AM LDT	10.1 H	09:54AM LDT	1.9 L	04:23PM LDT	8.7 H	09:39PM LDT	4.6 L		
04/30/2011	Sat	03:34AM LDT	10.1 H	10:20AM LDT	1.0 L	05:10PM LDT	9.3 H	10:23PM LDT	5.1 L		

All times are listed in Local Standard Time(LST) or, Local Daylight Time (LDT) (when applicable). All heights are in feet referenced to Mean Lower Low Water (MLLW).

May - Edmonds

Date	Day	Time	Height	Time	Height	Time	Height	Time	Height	Time	Height
05/01/2011	Sun	03:59AM LDT	10.1 H	10:45AM LDT	0.3 L	05:50PM LDT	9.8 H	11:03PM LDT	5.6 L		
05/02/2011	Mon	04:25AM LDT	10.0 H	11:11AM LDT	-0.4 L	06:26PM LDT	10.2 H	11:42PM LDT	6.1 L		
05/03/2011	Tue	04:53AM LDT	9.9 H	11:41AM LDT	-1.0 L	07:01PM LDT	10.6 H				
05/04/2011	Wed	12:20AM LDT	6.5 L	05:23AM LDT	9.8 H	12:15PM LDT	-1.4 L	07:38PM LDT	10.8 H		
05/05/2011	Thu	12:59AM LDT	6.8 L	05:55AM LDT	9.6 H	12:52PM LDT	-1.7 L	08:16PM LDT	10.8 H		
05/06/2011	Fri	01:41AM LDT	6.9 L	06:30AM LDT	9.4 H	01:32PM LDT	-1.7 L	08:59PM LDT	10.8 H		
05/07/2011	Sat	02:28AM LDT	7.0 L	07:09AM LDT	9.1 H	02:15PM LDT	-1.5 L	09:44PM LDT	10.8 H		
05/08/2011	Sun	03:20AM LDT	7.0 L	07:57AM LDT	8.7 H	03:03PM LDT	-1.1 L	10:33PM LDT	10.8 H		
05/09/2011	Mon	04:22AM LDT	6.7 L	08:58AM LDT	8.3 H	03:54PM LDT	-0.4 L	11:23PM LDT	10.7 H		
05/10/2011	Tue	05:30AM LDT	6.0 L	10:15AM LDT	7.8 H	04:50PM LDT	0.5 L				
05/11/2011	Wed	12:11AM LDT	10.8 H	06:37AM LDT	5.0 L	11:42AM LDT	7.6 H	05:52PM LDT	1.6 L		
05/12/2011	Thu	12:56AM LDT	10.8 H	07:34AM LDT	3.5 L	01:11PM LDT	7.8 H	06:57PM LDT	2.7 L		
05/13/2011	Fri	01:38AM LDT	11.0 H	08:23AM LDT	1.8 L	02:35PM LDT	8.4 H	08:02PM LDT	3.8 L		
05/14/2011	Sat	02:18AM LDT	11.2 H	09:08AM LDT	0.1 L	03:48PM LDT	9.3 H	09:05PM LDT	4.7 L		
05/15/2011	Sun	02:57AM LDT	11.4 H	09:52AM LDT	-1.4 L	04:52PM LDT	10.3 H	10:04PM LDT	5.4 L		
05/16/2011	Mon	03:37AM LDT	11.4 H	10:35AM LDT	-2.5 L	05:49PM LDT	10.9 H	11:00PM LDT	6.0 L		
05/17/2011	Tue	04:18AM LDT	11.3 H	11:18AM LDT	-3.2 L	06:41PM LDT	11.4 H	11:55PM LDT	6.4 L		
05/18/2011	Wed	05:01AM LDT	10.9 H	12:02PM LDT	-3.4 L	07:31PM LDT	11.6 H				
05/19/2011	Thu	12:50AM LDT	6.6 L	05:47AM LDT	10.6 H	12:46PM LDT	-3.1 L	08:20PM LDT	11.6 H		
05/20/2011	Fri	01:46AM LDT	6.6 L	06:36AM LDT	9.9 H	01:32PM LDT	-2.5 L	09:07PM LDT	11.5 H		
05/21/2011	Sat	02:46AM LDT	6.5 L	07:29AM LDT	9.1 H	02:18PM LDT	-1.6 L	09:54PM LDT	11.2 H		
05/22/2011	Sun	03:51AM LDT	6.1 L	08:28AM LDT	8.4 H	03:06PM LDT	-0.5 L	10:40PM LDT	11.0 H		
05/23/2011	Mon	05:00AM LDT	5.6 L	09:35AM LDT	7.6 H	03:56PM LDT	0.8 L	11:25PM LDT	10.8 H		
05/24/2011	Tue	06:10AM LDT	4.9 L	10:53AM LDT	7.0 H	04:50PM LDT	2.2 L				
05/25/2011	Wed	12:07AM LDT	10.6 H	07:09AM LDT	4.0 L	12:23PM LDT	6.8 H	05:49PM LDT	3.5 L		
05/26/2011	Thu	12:47AM LDT	10.4 H	07:57AM LDT	2.9 L	01:58PM LDT	7.1 H	06:54PM LDT	4.7 L		
05/27/2011	Fri	01:24AM LDT	10.3 H	08:36AM LDT	1.9 L	03:20PM LDT	7.9 H	08:01PM LDT	5.5 L		
05/28/2011	Sat	01:58AM LDT	10.2 H	09:08AM LDT	1.0 L	04:23PM LDT	8.6 H	09:03PM LDT	6.2 L		
05/29/2011	Sun	02:31AM LDT	10.0 H	09:38AM LDT	0.1 L	05:12PM LDT	9.4 H	09:58PM LDT	6.7 L		
05/30/2011	Mon	03:04AM LDT	10.0 H	10:08AM LDT	-0.7 L	05:52PM LDT	10.0 H	10:45PM LDT	7.1 L		
05/31/2011	Tue	03:37AM LDT	9.9 H	10:40AM LDT	-1.3 L	06:27PM LDT	10.5 H	11:27PM LDT	7.3 L		

All times are listed in Local Standard Time(LST) or, Local Daylight Time (LDT) (when applicable). All heights are in feet referenced to Mean Lower Low Water (MLLW).

June - Edmonds

Date	Day	Time	Height	Time	Height	Time	Height	Time	Height	Time	Height
06/01/2011	Wed	04:10AM LDT	9.8 H	11:14AM LDT	-1.9 L	07:00PM LDT	10.8 H				
06/02/2011	Thu	12:07AM LDT	7.4 L	04:46AM LDT	9.7 H	11:51AM LDT	-2.2 L	07:33PM LDT	11.0 H		
06/03/2011	Fri	12:47AM LDT	7.3 L	05:24AM LDT	9.6 H	12:30PM LDT	-2.4 L	08:08PM LDT	11.2 H		
06/04/2011	Sat	01:30AM LDT	7.2 L	06:06AM LDT	9.4 H	01:11PM LDT	-2.4 L	08:44PM LDT	11.3 H		
06/05/2011	Sun	02:16AM LDT	6.8 L	06:54AM LDT	9.1 H	01:55PM LDT	-2.0 L	09:22PM LDT	11.4 H		
06/06/2011	Mon	03:07AM LDT	6.3 L	07:50AM LDT	8.7 H	02:40PM LDT	-1.3 L	10:02PM LDT	11.4 H		
06/07/2011	Tue	04:03AM LDT	5.5 L	08:56AM LDT	8.2 H	03:28PM LDT	-0.1 L	10:42PM LDT	11.5 H		
06/08/2011	Wed	05:03AM LDT	4.6 L	10:13AM LDT	7.7 H	04:19PM LDT	1.3 L	11:23PM LDT	11.5 H		
06/09/2011	Thu	06:03AM LDT	3.2 L	11:40AM LDT	7.5 H	05:16PM LDT	2.9 L				
06/10/2011	Fri	12:05AM LDT	11.5 H	07:01AM LDT	1.7 L	01:15PM LDT	7.7 H	06:22PM LDT	4.5 L		
06/11/2011	Sat	12:48AM LDT	11.4 H	07:54AM LDT	0.2 L	02:48PM LDT	8.4 H	07:35PM LDT	5.6 L		
06/12/2011	Sun	01:33AM LDT	11.4 H	08:44AM LDT	-1.2 L	04:07PM LDT	9.5 H	08:48PM LDT	6.5 L		
06/13/2011	Mon	02:18AM LDT	11.3 H	09:30AM LDT	-2.2 L	05:09PM LDT	10.4 H	09:55PM LDT	7.0 L		
06/14/2011	Tue	03:05AM LDT	11.1 H	10:16AM LDT	-2.9 L	06:00PM LDT	11.0 H	10:56PM LDT	7.1 L		
06/15/2011	Wed	03:52AM LDT	10.8 H	11:00AM LDT	-3.2 L	06:45PM LDT	11.4 H	11:52PM LDT	7.0 L		
06/16/2011	Thu	04:40AM LDT	10.6 H	11:44AM LDT	-3.2 L	07:27PM LDT	11.6 H				
06/17/2011	Fri	12:44AM LDT	6.8 L	05:29AM LDT	10.1 H	12:27PM LDT	-2.8 L	08:06PM LDT	11.6 H		
06/18/2011	Sat	01:36AM LDT	6.4 L	06:20AM LDT	9.5 H	01:10PM LDT	-2.1 L	08:42PM LDT	11.5 H		
06/19/2011	Sun	02:27AM LDT	6.0 L	07:13AM LDT	8.9 H	01:53PM LDT	-1.1 L	09:17PM LDT	11.4 H		
06/20/2011	Mon	03:19AM LDT	5.4 L	08:09AM LDT	8.3 H	02:35PM LDT	0.0 L	09:51PM LDT	11.2 H		
06/21/2011	Tue	04:13AM LDT	4.9 L	09:11AM LDT	7.6 H	03:17PM LDT	1.4 L	10:26PM LDT	11.0 H		
06/22/2011	Wed	05:07AM LDT	4.1 L	10:22AM LDT	7.1 H	04:02PM LDT	2.9 L	11:01PM LDT	10.8 H		
06/23/2011	Thu	06:00AM LDT	3.3 L	11:45AM LDT	6.9 H	04:52PM LDT	4.4 L	11:38PM LDT	10.6 H		
06/24/2011	Fri	06:50AM LDT	2.4 L	01:26PM LDT	7.1 H	05:52PM LDT	5.7 L				
06/25/2011	Sat	12:17AM LDT	10.3 H	07:35AM LDT	1.5 L	03:05PM LDT	7.9 H	07:07PM LDT	6.7 L		
06/26/2011	Sun	12:57AM LDT	10.1 H	08:17AM LDT	0.7 L	04:16PM LDT	8.7 H	08:27PM LDT	7.4 L		
06/27/2011	Mon	01:38AM LDT	9.9 H	08:56AM LDT	-0.2 L	05:05PM LDT	9.5 H	09:34PM LDT	7.7 L		
06/28/2011	Tue	02:19AM LDT	9.8 H	09:34AM LDT	-0.9 L	05:43PM LDT	10.1 H	10:26PM LDT	7.8 L		
06/29/2011	Wed	03:00AM LDT	9.8 H	10:12AM LDT	-1.6 L	06:15PM LDT	10.6 H	11:08PM LDT	7.7 L		
06/30/2011	Thu	03:42AM LDT	9.8 H	10:50AM LDT	-2.1 L	06:44PM LDT	10.8 H	11:47PM LDT	7.5 L		

All times are listed in Local Standard Time(LST) or, Local Daylight Time (LDT) (when applicable). All heights are in feet referenced to Mean Lower Low Water (MLLW).

July - Edmonds

Date	Day	Time	Height	Time	Height	Time	Height	Time	Height	Time	Height
07/01/2011	Fri	04:24AM LDT	9.9 H	11:30AM LDT	-2.5 L	07:13PM LDT	11.1 H				
07/02/2011	Sat	12:26AM LDT	7.1 L	05:10AM LDT	9.9 H	12:11PM LDT	-2.6 L	07:42PM LDT	11.3 H		
07/03/2011	Sun	01:07AM LDT	6.5 L	05:58AM LDT	9.7 H	12:52PM LDT	-2.4 L	08:14PM LDT	11.6 H		
07/04/2011	Mon	01:52AM LDT	5.8 L	06:52AM LDT	9.4 H	01:35PM LDT	-1.7 L	08:47PM LDT	11.8 H		
07/05/2011	Tue	02:41AM LDT	5.0 L	07:51AM LDT	8.9 H	02:19PM LDT	-0.6 L	09:22PM LDT	11.9 H		
07/06/2011	Wed	03:33AM LDT	3.9 L	08:57AM LDT	8.4 H	03:04PM LDT	0.9 L	09:59PM LDT	11.9 H		
07/07/2011	Thu	04:29AM LDT	2.7 L	10:12AM LDT	8.0 H	03:53PM LDT	2.6 L	10:38PM LDT	11.8 H		
07/08/2011	Fri	05:27AM LDT	1.6 L	11:40AM LDT	7.8 H	04:50PM LDT	4.4 L	11:21PM LDT	11.5 H		
07/09/2011	Sat	06:27AM LDT	0.5 L	01:23PM LDT	8.1 H	06:00PM LDT	5.9 L				
07/10/2011	Sun	12:09AM LDT	11.3 H	07:26AM LDT	-0.6 L	03:05PM LDT	8.9 H	07:24PM LDT	7.0 L		
07/11/2011	Mon	01:01AM LDT	11.0 H	08:21AM LDT	-1.4 L	04:19PM LDT	9.8 H	08:50PM LDT	7.4 L		
07/12/2011	Tue	01:55AM LDT	10.8 H	09:13AM LDT	-2.1 L	05:13PM LDT	10.6 H	10:01PM LDT	7.4 L		
07/13/2011	Wed	02:50AM LDT	10.6 H	10:01AM LDT	-2.4 L	05:57PM LDT	11.0 H	10:58PM LDT	7.0 L		
07/14/2011	Thu	03:44AM LDT	10.3 H	10:46AM LDT	-2.5 L	06:34PM LDT	11.2 H	11:47PM LDT	6.6 L		
07/15/2011	Fri	04:34AM LDT	10.1 H	11:29AM LDT	-2.2 L	07:06PM LDT	11.3 H				
07/16/2011	Sat	12:31AM LDT	6.1 L	05:24AM LDT	9.8 H	12:09PM LDT	-1.8 L	07:35PM LDT	11.3 H		
07/17/2011	Sun	01:13AM LDT	5.6 L	06:12AM LDT	9.4 H	12:49PM LDT	-1.1 L	08:02PM LDT	11.2 H		
07/18/2011	Mon	01:53AM LDT	5.0 L	07:01AM LDT	8.9 H	01:27PM LDT	-0.1 L	08:29PM LDT	11.2 H		
07/19/2011	Tue	02:34AM LDT	4.4 L	07:53AM LDT	8.4 H	02:04PM LDT	1.0 L	08:57PM LDT	11.1 H		
07/20/2011	Wed	03:16AM LDT	3.8 L	08:49AM LDT	8.1 H	02:42PM LDT	2.4 L	09:28PM LDT	10.9 H		
07/21/2011	Thu	04:00AM LDT	3.2 L	09:51AM LDT	7.7 H	03:22PM LDT	3.8 L	10:01PM LDT	10.7 H		
07/22/2011	Fri	04:46AM LDT	2.6 L	11:04AM LDT	7.4 H	04:06PM LDT	5.1 L	10:37PM LDT	10.3 H		
07/23/2011	Sat	05:36AM LDT	2.0 L	12:36PM LDT	7.5 H	05:01PM LDT	6.4 L	11:18PM LDT	10.0 H		
07/24/2011	Sun	06:29AM LDT	1.4 L	02:31PM LDT	8.1 H	06:21PM LDT	7.4 L				
07/25/2011	Mon	12:03AM LDT	9.6 H	07:23AM LDT	0.7 L	03:52PM LDT	8.8 H	07:58PM LDT	7.9 L		
07/26/2011	Tue	12:54AM LDT	9.5 H	08:13AM LDT	0.0 L	04:40PM LDT	9.5 H	09:14PM LDT	7.9 L		
07/27/2011	Wed	01:46AM LDT	9.4 H	09:01AM LDT	-0.7 L	05:14PM LDT	10.0 H	10:03PM LDT	7.6 L		
07/28/2011	Thu	02:37AM LDT	9.6 H	09:45AM LDT	-1.4 L	05:42PM LDT	10.4 H	10:42PM LDT	7.2 L		
07/29/2011	Fri	03:27AM LDT	9.8 H	10:28AM LDT	-1.9 L	06:07PM LDT	10.8 H	11:18PM LDT	6.6 L		
07/30/2011	Sat	04:16AM LDT	10.0 H	11:09AM LDT	-2.1 L	06:32PM LDT	11.0 H	11:57PM LDT	5.9 L		
07/31/2011	Sun	05:05AM LDT	10.2 H	11:51AM LDT	-2.0 L	06:59PM LDT	11.3 H				

All times are listed in Local Standard Time(LST) or, Local Daylight Time (LDT) (when applicable). All heights are in feet referenced to Mean Lower Low Water (MLLW).

August - Edmonds

Date	Day	Time	Height	Time	Height	Time	Height	Time	Height	Time	Height
08/01/2011	Mon	12:38AM LDT	5.0 L	05:58AM LDT	10.1 H	12:33PM LDT	-1.5 L	07:29PM LDT	11.6 H		
08/02/2011	Tue	01:22AM LDT	3.9 L	06:53AM LDT	9.9 H	01:15PM LDT	-0.5 L	08:01PM LDT	11.8 H		
08/03/2011	Wed	02:09AM LDT	2.8 L	07:53AM LDT	9.5 H	01:59PM LDT	0.9 L	08:36PM LDT	11.9 H		
08/04/2011	Thu	02:59AM LDT	1.8 L	08:58AM LDT	9.1 H	02:45PM LDT	2.5 L	09:14PM LDT	11.7 H		
08/05/2011	Fri	03:52AM LDT	0.9 L	10:12AM LDT	8.7 H	03:36PM LDT	4.3 L	09:56PM LDT	11.4 H		
08/06/2011	Sat	04:50AM LDT	0.3 L	11:41AM LDT	8.5 H	04:37PM LDT	5.7 L	10:44PM LDT	11.0 H		
08/07/2011	Sun	05:53AM LDT	-0.2 L	01:28PM LDT	8.7 H	05:59PM LDT	6.9 L	11:40PM LDT	10.5 H		
08/08/2011	Mon	06:58AM LDT	-0.6 L	03:04PM LDT	9.4 H	07:39PM LDT	7.4 L				
08/09/2011	Tue	12:44AM LDT	10.1 H	08:01AM LDT	-0.9 L	04:09PM LDT	10.1 H	09:05PM LDT	7.1 L		
08/10/2011	Wed	01:51AM LDT	9.9 H	08:58AM LDT	-1.1 L	04:56PM LDT	10.6 H	10:06PM LDT	6.6 L		
08/11/2011	Thu	02:54AM LDT	9.8 H	09:48AM LDT	-1.2 L	05:33PM LDT	10.8 H	10:53PM LDT	5.9 L		
08/12/2011	Fri	03:49AM LDT	9.7 H	10:33AM LDT	-1.1 L	06:02PM LDT	10.8 H	11:32PM LDT	5.3 L		
08/13/2011	Sat	04:39AM LDT	9.7 H	11:13AM LDT	-0.8 L	06:27PM LDT	10.8 H				
08/14/2011	Sun	12:07AM LDT	4.8 L	05:25AM LDT	9.5 H	11:50AM LDT	-0.2 L	06:48PM LDT	10.8 H		
08/15/2011	Mon	12:40AM LDT	4.1 L	06:10AM LDT	9.4 H	12:26PM LDT	0.5 L	07:10PM LDT	10.8 H		
08/16/2011	Tue	01:12AM LDT	3.5 L	06:54AM LDT	9.2 H	01:01PM LDT	1.5 L	07:34PM LDT	10.8 H		
08/17/2011	Wed	01:46AM LDT	2.9 L	07:41AM LDT	9.0 H	01:37PM LDT	2.5 L	08:01PM LDT	10.7 H		
08/18/2011	Thu	02:22AM LDT	2.3 L	08:30AM LDT	8.7 H	02:13PM LDT	3.7 L	08:31PM LDT	10.5 H		
08/19/2011	Fri	03:00AM LDT	1.9 L	09:24AM LDT	8.5 H	02:52PM LDT	4.9 L	09:03PM LDT	10.1 H		
08/20/2011	Sat	03:44AM LDT	1.6 L	10:27AM LDT	8.4 H	03:36PM LDT	5.9 L	09:39PM LDT	9.7 H		
08/21/2011	Sun	04:32AM LDT	1.4 L	11:45AM LDT	8.2 H	04:32PM LDT	6.9 L	10:22PM LDT	9.3 H		
08/22/2011	Mon	05:28AM LDT	1.2 L	01:27PM LDT	8.4 H	05:56PM LDT	7.6 L	11:15PM LDT	8.9 H		
08/23/2011	Tue	06:29AM LDT	0.9 L	02:58PM LDT	8.8 H	07:40PM LDT	7.7 L				
08/24/2011	Wed	12:19AM LDT	8.8 H	07:30AM LDT	0.4 L	03:49PM LDT	9.4 H	08:51PM LDT	7.4 L		
08/25/2011	Thu	01:24AM LDT	8.9 H	08:26AM LDT	-0.2 L	04:21PM LDT	9.9 H	09:35PM LDT	6.8 L		
08/26/2011	Fri	02:24AM LDT	9.3 H	09:16AM LDT	-0.7 L	04:47PM LDT	10.3 H	10:12PM LDT	5.9 L		
08/27/2011	Sat	03:19AM LDT	9.7 H	10:02AM LDT	-1.0 L	05:12PM LDT	10.7 H	10:48PM LDT	5.0 L		
08/28/2011	Sun	04:13AM LDT	10.1 H	10:46AM LDT	-0.9 L	05:38PM LDT	11.0 H	11:26PM LDT	3.8 L		
08/29/2011	Mon	05:05AM LDT	10.4 H	11:28AM LDT	-0.5 L	06:07PM LDT	11.3 H				
08/30/2011	Tue	12:07AM LDT	2.5 L	05:59AM LDT	10.6 H	12:12PM LDT	0.4 L	06:38PM LDT	11.5 H		
08/31/2011	Wed	12:50AM LDT	1.3 L	06:56AM LDT	10.5 H	12:56PM LDT	1.6 L	07:12PM LDT	11.6 H		

All times are listed in Local Standard Time(LST) or, Local Daylight Time (LDT) (when applicable). All heights are in feet referenced to Mean Lower Low Water (MLLW).

September - Edmonds

Date	Day	Time	Height	Time	Height	Time	Height	Time	Height	Time	Height
09/01/2011	Thu	01:36AM LDT	0.3 L	07:55AM LDT	10.3 H	01:42PM LDT	2.9 L	07:49PM LDT	11.5 H		
09/02/2011	Fri	02:25AM LDT	-0.4 L	08:59AM LDT	10.0 H	02:32PM LDT	4.4 L	08:30PM LDT	11.2 H		
09/03/2011	Sat	03:17AM LDT	-0.7 L	10:11AM LDT	9.6 H	03:29PM LDT	5.6 L	09:17PM LDT	10.7 H		
09/04/2011	Sun	04:15AM LDT	-0.6 L	11:36AM LDT	9.4 H	04:41PM LDT	6.6 L	10:13PM LDT	10.0 H		
09/05/2011	Mon	05:19AM LDT	-0.3 L	01:15PM LDT	9.5 H	06:19PM LDT	7.0 L	11:22PM LDT	9.4 H		
09/06/2011	Tue	06:28AM LDT	-0.1 L	02:37PM LDT	9.8 H	08:00PM LDT	6.7 L				
09/07/2011	Wed	12:41AM LDT	9.0 H	07:37AM LDT	0.1 L	03:35PM LDT	10.2 H	09:09PM LDT	5.9 L		
09/08/2011	Thu	01:58AM LDT	8.9 H	08:39AM LDT	0.2 L	04:17PM LDT	10.5 H	09:58PM LDT	5.1 L		
09/09/2011	Fri	03:05AM LDT	9.0 H	09:31AM LDT	0.3 L	04:49PM LDT	10.5 H	10:36PM LDT	4.4 L		
09/10/2011	Sat	04:00AM LDT	9.2 H	10:15AM LDT	0.7 L	05:13PM LDT	10.5 H	11:08PM LDT	3.6 L		
09/11/2011	Sun	04:47AM LDT	9.4 H	10:54AM LDT	1.2 L	05:33PM LDT	10.5 H	11:37PM LDT	2.9 L		
09/12/2011	Mon	05:30AM LDT	9.5 H	11:30AM LDT	1.8 L	05:52PM LDT	10.5 H				
09/13/2011	Tue	12:04AM LDT	2.3 L	06:11AM LDT	9.6 H	12:04PM LDT	2.6 L	06:13PM LDT	10.4 H		
09/14/2011	Wed	12:32AM LDT	1.6 L	06:51AM LDT	9.7 H	12:39PM LDT	3.5 L	06:38PM LDT	10.3 H		
09/15/2011	Thu	01:02AM LDT	1.1 L	07:33AM LDT	9.7 H	01:14PM LDT	4.3 L	07:06PM LDT	10.1 H		
09/16/2011	Fri	01:35AM LDT	0.7 L	08:17AM LDT	9.6 H	01:52PM LDT	5.1 L	07:35PM LDT	9.8 H		
09/17/2011	Sat	02:13AM LDT	0.5 L	09:05AM LDT	9.5 H	02:33PM LDT	5.9 L	08:08PM LDT	9.4 H		
09/18/2011	Sun	02:54AM LDT	0.5 L	10:00AM LDT	9.3 H	03:21PM LDT	6.6 L	08:44PM LDT	9.0 H		
09/19/2011	Mon	03:42AM LDT	0.6 L	11:05AM LDT	9.1 H	04:22PM LDT	7.2 L	09:29PM LDT	8.6 H		
09/20/2011	Tue	04:37AM LDT	0.8 L	12:25PM LDT	9.0 H	05:49PM LDT	7.4 L	10:32PM LDT	8.3 H		
09/21/2011	Wed	05:40AM LDT	0.8 L	01:42PM LDT	9.3 H	07:23PM LDT	7.1 L	11:51PM LDT	8.2 H		
09/22/2011	Thu	06:45AM LDT	0.8 L	02:36PM LDT	9.6 H	08:23PM LDT	6.4 L				
09/23/2011	Fri	01:07AM LDT	8.4 H	07:47AM LDT	0.6 L	03:13PM LDT	10.0 H	09:04PM LDT	5.4 L		
09/24/2011	Sat	02:15AM LDT	8.8 H	08:43AM LDT	0.5 L	03:43PM LDT	10.5 H	09:41PM LDT	4.2 L		
09/25/2011	Sun	03:16AM LDT	9.5 H	09:33AM LDT	0.7 L	04:12PM LDT	10.8 H	10:18PM LDT	2.7 L		
09/26/2011	Mon	04:13AM LDT	10.1 H	10:20AM LDT	1.1 L	04:42PM LDT	11.1 H	10:57PM LDT	1.2 L		
09/27/2011	Tue	05:08AM LDT	10.7 H	11:06AM LDT	1.9 L	05:14PM LDT	11.4 H	11:38PM LDT	-0.2 L		
09/28/2011	Wed	06:03AM LDT	11.0 H	11:52AM LDT	2.8 L	05:48PM LDT	11.5 H				
09/29/2011	Thu	12:21AM LDT	-1.2 L	06:59AM LDT	11.1 H	12:40PM LDT	3.9 L	06:25PM LDT	11.5 H		
09/30/2011	Fri	01:06AM LDT	-1.9 L	07:57AM LDT	11.1 H	01:30PM LDT	4.9 L	07:06PM LDT	11.1 H		

All times are listed in Local Standard Time(LST) or, Local Daylight Time (LDT) (when applicable). All heights are in feet referenced to Mean Lower Low Water (MLLW).

October - Edmonds

Date	Day	Time	Height	Time	Height	Time	Height	Time	Height	Time	Height
10/01/2011	Sat	01:54AM LDT	-2.0 L	08:58AM LDT	10.8 H	02:26PM LDT	5.8 L	07:52PM LDT	10.6 H		
10/02/2011	Sun	02:46AM LDT	-1.7 L	10:06AM LDT	10.6 H	03:31PM LDT	6.5 L	08:45PM LDT	9.8 H		
10/03/2011	Mon	03:42AM LDT	-1.0 L	11:22AM LDT	10.3 H	04:54PM LDT	6.8 L	09:50PM LDT	9.0 H		
10/04/2011	Tue	04:44AM LDT	-0.1 L	12:42PM LDT	10.2 H	06:35PM LDT	6.4 L	11:10PM LDT	8.4 H		
10/05/2011	Wed	05:54AM LDT	0.7 L	01:51PM LDT	10.2 H	07:58PM LDT	5.6 L				
10/06/2011	Thu	12:40AM LDT	8.1 H	07:05AM LDT	1.3 L	02:43PM LDT	10.4 H	08:54PM LDT	4.7 L		
10/07/2011	Fri	02:04AM LDT	8.2 H	08:10AM LDT	1.8 L	03:22PM LDT	10.4 H	09:36PM LDT	3.6 L		
10/08/2011	Sat	03:13AM LDT	8.5 H	09:05AM LDT	2.3 L	03:51PM LDT	10.4 H	10:10PM LDT	2.7 L		
10/09/2011	Sun	04:09AM LDT	9.0 H	09:52AM LDT	2.8 L	04:14PM LDT	10.4 H	10:38PM LDT	1.9 L		
10/10/2011	Mon	04:56AM LDT	9.4 H	10:33AM LDT	3.5 L	04:34PM LDT	10.3 H	11:04PM LDT	1.2 L		
10/11/2011	Tue	05:38AM LDT	9.8 H	11:10AM LDT	4.2 L	04:56PM LDT	10.3 H	11:29PM LDT	0.5 L		
10/12/2011	Wed	06:15AM LDT	10.1 H	11:46AM LDT	4.8 L	05:20PM LDT	10.1 H	11:55PM LDT	0.0 L		
10/13/2011	Thu	06:52AM LDT	10.3 H	12:22PM LDT	5.4 L	05:46PM LDT	10.0 H				
10/14/2011	Fri	12:25AM LDT	-0.4 L	07:29AM LDT	10.5 H	12:59PM LDT	5.9 L	06:15PM LDT	9.7 H		
10/15/2011	Sat	12:59AM LDT	-0.6 L	08:08AM LDT	10.5 H	01:39PM LDT	6.4 L	06:45PM LDT	9.4 H		
10/16/2011	Sun	01:36AM LDT	-0.6 L	08:52AM LDT	10.4 H	02:23PM LDT	6.8 L	07:19PM LDT	9.1 H		
10/17/2011	Mon	02:18AM LDT	-0.5 L	09:41AM LDT	10.3 H	03:14PM LDT	7.1 L	07:57PM LDT	8.6 H		
10/18/2011	Tue	03:04AM LDT	-0.2 L	10:37AM LDT	10.1 H	04:18PM LDT	7.2 L	08:47PM LDT	8.3 H		
10/19/2011	Wed	03:57AM LDT	0.3 L	11:37AM LDT	10.0 H	05:37PM LDT	7.0 L	10:00PM LDT	7.9 H		
10/20/2011	Thu	04:56AM LDT	0.8 L	12:35PM LDT	10.1 H	06:53PM LDT	6.3 L	11:28PM LDT	7.7 H		
10/21/2011	Fri	05:59AM LDT	1.3 L	01:24PM LDT	10.3 H	07:48PM LDT	5.1 L				
10/22/2011	Sat	12:54AM LDT	7.9 H	07:04AM LDT	1.8 L	02:05PM LDT	10.6 H	08:31PM LDT	3.8 L		
10/23/2011	Sun	02:10AM LDT	8.4 H	08:05AM LDT	2.3 L	02:41PM LDT	10.9 H	09:11PM LDT	2.1 L		
10/24/2011	Mon	03:18AM LDT	9.3 H	09:02AM LDT	3.0 L	03:15PM LDT	11.2 H	09:51PM LDT	0.4 L		
10/25/2011	Tue	04:19AM LDT	10.2 H	09:55AM LDT	3.7 L	03:50PM LDT	11.5 H	10:31PM LDT	-1.1 L		
10/26/2011	Wed	05:15AM LDT	10.9 H	10:46AM LDT	4.5 L	04:26PM LDT	11.7 H	11:13PM LDT	-2.3 L		
10/27/2011	Thu	06:09AM LDT	11.4 H	11:36AM LDT	5.2 L	05:05PM LDT	11.6 H	11:56PM LDT	-3.0 L		
10/28/2011	Fri	07:03AM LDT	11.7 H	12:29PM LDT	5.8 L	05:46PM LDT	11.3 H				
10/29/2011	Sat	12:42AM LDT	-3.2 L	07:58AM LDT	11.8 H	01:23PM LDT	6.3 L	06:32PM LDT	10.8 H		
10/30/2011	Sun	01:29AM LDT	-2.8 L	08:54AM LDT	11.6 H	02:23PM LDT	6.7 L	07:22PM LDT	10.1 H		
10/31/2011	Mon	02:19AM LDT	-2.1 L	09:53AM LDT	11.3 H	03:32PM LDT	6.7 L	08:20PM LDT	9.2 H		

All times are listed in Local Standard Time(LST) or, Local Daylight Time (LDT) (when applicable). All heights are in feet referenced to Mean Lower Low Water (MLLW).

November - Edmonds

Date	Day	Time	Height	Time	Height	Time	Height	Time	Height	Time	Height
11/01/2011	Tue	03:12AM LDT	-1.0 L	10:53AM LDT	11.0 H	04:54PM LDT	6.4 L	09:30PM LDT	8.4 H		
11/02/2011	Wed	04:09AM LDT	0.2 L	11:54AM LDT	10.8 H	06:21PM LDT	5.7 L	10:54PM LDT	7.7 H		
11/03/2011	Thu	05:11AM LDT	1.5 L	12:49PM LDT	10.8 H	07:32PM LDT	4.7 L				
11/04/2011	Fri	12:29AM LDT	7.4 H	06:19AM LDT	2.6 L	01:36PM LDT	10.7 H	08:24PM LDT	3.6 L		
11/05/2011	Sat	02:01AM LDT	7.7 H	07:27AM LDT	3.6 L	02:13PM LDT	10.6 H	09:04PM LDT	2.5 L		
11/06/2011	Sun	02:17AM LST	8.3 H	07:30AM LST	4.4 L	01:44PM LST	10.5 H	08:36PM LST	1.6 L		
11/07/2011	Mon	03:17AM LST	9.0 H	08:24AM LST	5.0 L	02:12PM LST	10.4 H	09:04PM LST	0.7 L		
11/08/2011	Tue	04:05AM LST	9.7 H	09:12AM LST	5.7 L	02:38PM LST	10.3 H	09:30PM LST	0.0 L		
11/09/2011	Wed	04:46AM LST	10.2 H	09:54AM LST	6.2 L	03:05PM LST	10.2 H	09:56PM LST	-0.6 L		
11/10/2011	Thu	05:21AM LST	10.6 H	10:34AM LST	6.6 L	03:33PM LST	10.1 H	10:25PM LST	-1.0 L		
11/11/2011	Fri	05:54AM LST	10.8 H	11:12AM LST	7.0 L	04:03PM LST	9.9 H	10:57PM LST	-1.3 L		
11/12/2011	Sat	06:27AM LST	11.0 H	11:50AM LST	7.2 L	04:34PM LST	9.7 H	11:32PM LST	-1.5 L		
11/13/2011	Sun	07:03AM LST	11.1 H	12:31PM LST	7.3 L	05:08PM LST	9.4 H				
11/14/2011	Mon	12:11AM LST	-1.4 L	07:42AM LST	11.1 H	01:15PM LST	7.4 L	05:46PM LST	9.1 H		
11/15/2011	Tue	12:52AM LST	-1.2 L	08:24AM LST	11.1 H	02:06PM LST	7.2 L	06:31PM LST	8.7 H		
11/16/2011	Wed	01:36AM LST	-0.7 L	09:08AM LST	11.1 H	03:04PM LST	6.9 L	07:29PM LST	8.3 H		
11/17/2011	Thu	02:24AM LST	0.0 L	09:54AM LST	11.0 H	04:08PM LST	6.2 L	08:44PM LST	7.8 H		
11/18/2011	Fri	03:17AM LST	1.0 L	10:40AM LST	11.1 H	05:12PM LST	5.2 L	10:12PM LST	7.5 H		
11/19/2011	Sat	04:15AM LST	2.2 L	11:23AM LST	11.2 H	06:08PM LST	3.8 L	11:44PM LST	7.7 H		
11/20/2011	Sun	05:20AM LST	3.4 L	12:05PM LST	11.3 H	06:57PM LST	2.2 L				
11/21/2011	Mon	01:11AM LST	8.4 H	06:27AM LST	4.5 L	12:46PM LST	11.5 H	07:42PM LST	0.4 L		
11/22/2011	Tue	02:26AM LST	9.3 H	07:33AM LST	5.3 L	01:26PM LST	11.7 H	08:26PM LST	-1.1 L		
11/23/2011	Wed	03:31AM LST	10.4 H	08:35AM LST	6.1 L	02:07PM LST	11.8 H	09:09PM LST	-2.4 L		
11/24/2011	Thu	04:27AM LST	11.2 H	09:32AM LST	6.6 L	02:49PM LST	11.8 H	09:52PM LST	-3.2 L		
11/25/2011	Fri	05:18AM LST	11.8 H	10:28AM LST	6.9 L	03:33PM LST	11.5 H	10:37PM LST	-3.6 L		
11/26/2011	Sat	06:07AM LST	12.2 H	11:23AM LST	7.1 L	04:20PM LST	11.1 H	11:22PM LST	-3.4 L		
11/27/2011	Sun	06:55AM LST	12.2 H	12:19PM LST	7.0 L	05:10PM LST	10.6 H				
11/28/2011	Mon	12:08AM LST	-2.8 L	07:42AM LST	12.1 H	01:17PM LST	6.8 L	06:03PM LST	9.9 H		
11/29/2011	Tue	12:55AM LST	-1.9 L	08:28AM LST	11.9 H	02:20PM LST	6.4 L	07:02PM LST	9.0 H		
11/30/2011	Wed	01:43AM LST	-0.6 L	09:14AM LST	11.7 H	03:28PM LST	5.8 L	08:10PM LST	8.2 H		

All times are listed in Local Standard Time(LST) or, Local Daylight Time (LDT) (when applicable). All heights are in feet referenced to Mean Lower Low Water (MLLW).

December - Edmonds

Date	Day	Time	Height	Time	Height	Time	Height	Time	Height	Time	Height
12/01/2011	Thu	02:32AM LST	0.8 L	09:58AM LST	11.4 H	04:38PM LST	5.0 L	09:29PM LST	7.5 H		
12/02/2011	Fri	03:25AM LST	2.4 L	10:41AM LST	11.2 H	05:42PM LST	4.1 L	11:03PM LST	7.2 H		
12/03/2011	Sat	04:23AM LST	3.9 L	11:22AM LST	10.9 H	06:35PM LST	3.1 L				
12/04/2011	Sun	12:46AM LST	7.5 H	05:31AM LST	5.2 L	12:01PM LST	10.8 H	07:18PM LST	2.0 L		
12/05/2011	Mon	02:15AM LST	8.3 H	06:45AM LST	6.2 L	12:38PM LST	10.6 H	07:54PM LST	1.1 L		
12/06/2011	Tue	03:21AM LST	9.2 H	07:55AM LST	7.0 L	01:13PM LST	10.4 H	08:26PM LST	0.3 L		
12/07/2011	Wed	04:10AM LST	10.0 H	08:54AM LST	7.4 L	01:48PM LST	10.3 H	08:56PM LST	-0.4 L		
12/08/2011	Thu	04:49AM LST	10.6 H	09:44AM LST	7.7 L	02:23PM LST	10.2 H	09:27PM LST	-0.9 L		
12/09/2011	Fri	05:23AM LST	11.0 H	10:25AM LST	7.8 L	02:57PM LST	10.1 H	10:00PM LST	-1.4 L		
12/10/2011	Sat	05:53AM LST	11.3 H	11:03AM LST	7.8 L	03:33PM LST	10.0 H	10:35PM LST	-1.7 L		
12/11/2011	Sun	06:22AM LST	11.5 H	11:39AM LST	7.8 L	04:10PM LST	9.9 H	11:12PM LST	-1.8 L		
12/12/2011	Mon	06:52AM LST	11.6 H	12:17PM LST	7.5 L	04:50PM LST	9.7 H	11:51PM LST	-1.8 L		
12/13/2011	Tue	07:24AM LST	11.8 H	12:59PM LST	7.2 L	05:34PM LST	9.4 H				
12/14/2011	Wed	12:31AM LST	-1.4 L	07:58AM LST	11.9 H	01:45PM LST	6.7 L	06:25PM LST	9.0 H		
12/15/2011	Thu	01:13AM LST	-0.7 L	08:33AM LST	11.9 H	02:36PM LST	5.9 L	07:25PM LST	8.5 H		
12/16/2011	Fri	01:57AM LST	0.4 L	09:10AM LST	12.0 H	03:31PM LST	5.0 L	08:38PM LST	8.0 H		
12/17/2011	Sat	02:44AM LST	1.8 L	09:49AM LST	12.0 H	04:29PM LST	3.8 L	10:02PM LST	7.7 H		
12/18/2011	Sun	03:37AM LST	3.4 L	10:30AM LST	11.9 H	05:27PM LST	2.4 L	11:38PM LST	7.9 H		
12/19/2011	Mon	04:40AM LST	5.0 L	11:13AM LST	11.9 H	06:22PM LST	0.9 L				
12/20/2011	Tue	01:18AM LST	8.5 H	05:54AM LST	6.4 L	11:59AM LST	11.8 H	07:14PM LST	-0.5 L		
12/21/2011	Wed	02:43AM LST	9.7 H	07:13AM LST	7.3 L	12:47PM LST	11.7 H	08:04PM LST	-1.7 L		
12/22/2011	Thu	03:47AM LST	10.7 H	08:26AM LST	7.7 L	01:36PM LST	11.6 H	08:51PM LST	-2.6 L		
12/23/2011	Fri	04:38AM LST	11.5 H	09:30AM LST	7.8 L	02:26PM LST	11.5 H	09:37PM LST	-3.1 L		
12/24/2011	Sat	05:22AM LST	12.0 H	10:26AM LST	7.6 L	03:17PM LST	11.3 H	10:22PM LST	-3.1 L		
12/25/2011	Sun	06:03AM LST	12.2 H	11:18AM LST	7.2 L	04:08PM LST	10.9 H	11:06PM LST	-2.8 L		
12/26/2011	Mon	06:41AM LST	12.3 H	12:09PM LST	6.8 L	05:00PM LST	10.5 H	11:50PM LST	-2.1 L		
12/27/2011	Tue	07:17AM LST	12.3 H	12:59PM LST	6.2 L	05:53PM LST	9.8 H				
12/28/2011	Wed	12:33AM LST	-1.1 L	07:52AM LST	12.2 H	01:50PM LST	5.6 L	06:49PM LST	9.1 H		
12/29/2011	Thu	01:15AM LST	0.2 L	08:26AM LST	12.0 H	02:43PM LST	5.0 L	07:50PM LST	8.4 H		
12/30/2011	Fri	01:57AM LST	1.7 L	09:00AM LST	11.7 H	03:37PM LST	4.3 L	08:59PM LST	7.8 H		
12/31/2011	Sat	02:40AM LST	3.3 L	09:36AM LST	11.4 H	04:31PM LST	3.6 L	10:23PM LST	7.4 H		

All times are listed in Local Standard Time(LST) or, Local Daylight Time (LDT) (when applicable). All heights are in feet referenced to Mean Lower Low Water (MLLW).

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Appendix **B**

Stilling Well Construction

Stilling Well Installation

A stilling well will be mounted on a nearby dock, and a pressure transducer will be installed inside the stilling well. The purpose of a stilling well is to “still” the water around the pressure transducer in order to get accurate surface-water-level readings. Stilling the water reduces the scatter caused by wave action on the surface of the Puget Sound. However, the water inside the well must be able to fluctuate with rising or falling water levels. Holes drilled along the length of the well, as described below, or slotted PVC allow water inside the stilling well to more quickly equalize to the Puget Sound with changes in stage of water levels.

Materials:

- 10-foot sections of 2-inch-diameter PVC pipe (number of sections dependent on height of dock) – piping with pre-drilled holes (eg slotted) is preferable;
- PVC pipe couplers;
- PVC or similar end cap;
- 2-foot-long pipe straps (three per 10-foot section of PVC pipe);
- 2-inch wood screws (four per 10-foot section of PVC pipe);
- ¾-inch x ¼-inch-diameter toggle bolts with washers and nuts;
- 1-inch-diameter drill bit;
- •-inch-diameter drill bit;
- drill;
- hack saw;
- silicon caulk;
- PVC cement;
- two crescent wrenches or strap wrenches;
- manual water level indicator;
- data-logging pressure transducer (transducer); and
- proper PPE for each step, including safety glasses, leather gloves, steel-toed boots, and personal floatation devices.

Construction:

1. Field-verify the location of the stilling well. The location should allow for the well to be strapped flush with a wooden piling and should sit a few inches above the sediment surface. The water depth should adequately cover the transducer as it hangs in the well to minimize the risk of the water level falling below the bottom of the transducer. The piling should be accessible from the top of the dock so that the transducer can be accessed for data downloads.

2. If the available piping does not have holes in it, continue with this step. If the piping is pre-drilled, continue with Step 3. Starting 1 foot from the bottom of the piping, drill a 1-inch-diameter hole every 1 foot of depth. Line up the holes on the same side of the pipe. Place the holes to the pile, facing opposite of the river, to shield the openings from wave action.

3. If more than one 10-foot section of piping is being used, join the sections using the pipe couplers and the PVC cement. Be sure to line up the holes on each section of pipe. Allow the cement to dry according to the cement material instructions.

4. Attach the pipe straps to the PVC pipe at the middle and the top of each pipe section. The middle strap should be far enough up the pipe so that the stilling well can be strapped onto the pilings above the water surface. The straps **MUST** be secured to the PVC pipe to avoid slippage of the well through the straps. Center the strap on the pipe so that 1 foot of strap extends from the pipe in each direction. Attach the straps to the pipe by drilling two •-inch holes approximately 3 horizontal inches apart and bolting the straps in place using the toggle bolts.

5. Drill a 1-inch hole in the end cap through which the transducer will be fed. Alternatively, obtain a vented well cap for 2-inch well from In-Situ which allows for secure placement of transducer at top of stilling well.

Installation:

1. Use a boat or barge in the Sound to access the wooden piling. At least two people should be available for installation from the Sound side, and one person on the dock. From the Puget Sound, lift the stilling well into place. Lower it to within 3 inches of the sediment surface.

2. Wrap the pipe straps around the sides of the piling and secure into place using the drill and wood screws. Check that the holes in the piping are turned toward the piling but are not obstructed by the piling. Water should be able to flow freely in and out of the well through the holes. The top of the stilling well should be accessible from the dock. Use the additional unattached pipe straps, as necessary, to secure the well onto the piling in additional places.

3. Using a manual water level indicator, determine the water level from the top of the dock, as well as the depth to sediment, and record in the field notebook. Secure the end cap on the top of the stilling well using PVC cement or silicone caulk. Feed the transducer through the hole in the end cap, measuring the length of cable as it is let out. Hang the transducer at least 6 inches above the sediment and at least 4 feet below the water level, depending on the Puget Sound stage at the time of installation. **The transducer should hang sufficiently below the water level so that the water level does not fall below the transducer during the period of data collection.**

4. Once the transducer is in place, secure the transducer cable to the end cap and to a second location on the top of the dock. Use silicone caulk around the hole in the end cap to prevent the cable from slipping down the hole. All water levels measured are relative to the installation height of the transducer. **Any vertical movement of the transducer will invalidate the data collected.**

5. Following the manufacturer's instructions, connect the transducer to the computer housing the data collection software. Record the initial depth reading from the transducer. This depth reading, along with the initial measured water level, will be used as the baseline to calibrate the transducer to all future data collection. Steps 3 through 5 should be completed in rapid sequence in order to calculate the correct baseline. To verify the calculation, take a second surface-water level reading off the side of the dock.

6. Once the transducer baseline depth has been verified, set the collection intervals and period of data collection using the transducer software and start the logging data with the transducer. Disconnect the transducer from the computer.

7. Return to the transducer, as necessary, to download data.

Appendix **C**

Single-Well Pumping Test SOP

ARCADIS
Infrastructure, environment, facilities

Imagine the result

Specific Capacity Testing and Data Reduction

Rev. #: 2

Rev Date: February 3, 2006

Approval Signatures

Prepared by: Michael J Gefell Date: 2/27/09
Michael Gefell

Reviewed by: J Shi Date: 2/27/09
Jerry Shi (Technical Expert)

I. Scope and Application

Specific-capacity testing is a field method used to estimate the transmissivity of a saturated geologic medium surrounding the screened or open interval of a well. A specific-capacity test involves pumping groundwater from a well at a constant rate and quantifying the pumping rate and magnitude of drawdown inside the tested well after a known duration of pumping. Specific-capacity tests are also referred to as single-well pumping tests or constant-rate tests.

The transmissivity is calculated based on the pumping rate and drawdown measured inside the pumped well. Time-drawdown analysis can be performed with a semilog data plot to estimated transmissivity (Driscoll, 1986). Alternatively, an iterative calculation can be performed based on the pumping duration, the effective radius of the well, and storativity of the formation.

If the thickness of the effective water-bearing zone transmitting groundwater to the well intake is assumed to be approximately equal to the length of the intake, the hydraulic conductivity (K) can be estimated by dividing the transmissivity by the length of the intake.

II. Personnel Qualifications

Specific-capacity tests will be performed by persons who have been trained in the proper usage of pumping and water-level measurement equipment under the guidance of an experienced field geologist, engineer, or technician.

III. Equipment List

The equipment needed for specific-capacity testing includes:

- health and safety equipment, as required in the site Health and Safety Plan (HASP);
- cleaning equipment;
- pump (preferably submersible) capable of pumping at a controlled rate between a fraction of one gallon per minute (gpm) and several gpm, equipped with discharge line;
- power source for the pump;
- calibrated in-line totalizing flow meter or two calibrated buckets;

- stopwatch;
- electronic water-level indicator; and
- field notebook.

IV. Cautions

Wells and piezometers have different water-yielding characteristics as a function of their screen lengths, depth below the water table, and geologic materials in which they are installed. During the first minute of pumping, the water level should be continuously monitored and the pumping rate adjusted to avoid pumping the well dry. Additional cautionary statements pertinent to data reduction are included in Section I. Allowing discharge water to infiltrate next to the well can impact the test results and should be avoided.

V. Health and Safety Considerations

Field activities associated with specific-capacity testing will be performed in accordance with a site-specific HASP, a copy of which will be present on-site during such activities.

VI. Procedures

Pre-Test Set-Up

Prior to installing the pump into the well to be tested, the static water level inside the well is measured to the nearest 0.01 foot relative to a specified datum at the top of the well using the electronic water-level indicator. The water level and the time of measurement are recorded in the field notebook. The water level is measured again several minutes after the initial measurement. This measurement and time are also recorded. This procedure is repeated until two consecutive measurements are identical, indicating approximately static conditions. The static depth-to-water is recorded.

The pump is installed inserted into the well to at least 10 feet below the static water level, or within approximately 1 foot of the bottom of the well if the initial water column in the well is less than 11 feet. The depth of the pump intake below the static water level (indicating the length of the pre-test water column above the pump) is recorded. After the pump is installed inserted (but prior to pumping), the water level in the well is monitored until it has returned to within 0.01 foot of the static water level.

Test Procedures

The specific-capacity test is performed as follows:

1. Hold the water-level probe in the well just above the static water level. If an in-line totalizing flow meter is used, record the pre-test volume measurement in the field notebook. If no in-line flow meter is available, place the end of the discharge line into one of the two calibrated buckets. Record the total volumetric capacity of each bucket.

2. Simultaneously start the pump and stopwatch. Record the start time.

3. Immediately begin monitoring the water level in the well. If the water level inside the test well declines rapidly, quickly reduce the pumping rate to a slower, constant rate. To avoid pumping the well “dry” during the test, the drawdown after one minute of pumping should be less than or equal to 20% of the height of the pre-pumping water column above the pump. All pumping rate adjustments should be completed within 1 or 2 minutes of the start of pumping, after which no adjustment should be made other than minor adjustments that may be necessary to maintain a steady pumping rate.

4. Continue to pump for at least 20 minutes, recording the water level in the well at least once every 3 minutes during pumping. If an in-line flow meter is used, record the volume measurement on the totalizer gauge approximately every 2 minutes during the test. If calibrated buckets are used to measure the pumping rate, record the time at which the bucket reaches the known volumetric capacity of the bucket. Transfer the discharge line to the other (empty) calibrated bucket and record the time when it becomes full. Repeat this procedure for the duration of the test.

5. The specific-capacity test is complete after at least 20 minutes of pumping have elapsed. A longer pumping period is not necessary to estimate transmissivity from the test. However, increasing the length of the test may further increase the reliability of the resulting transmissivity estimate. Immediately before termination of pumping, record the final water-level measurement plus the time of the measurement.

6. Recovery data may be collected following pumping. Such data are highly recommended if the test well is in a location that may be tidally influenced. Also, recovery data provide backup data that may be used to estimate transmissivity. To collect recovery data, measure and record water level data according to the same schedule as used during pumping.

7. Calculate and record the total volume of groundwater removed from the well during the test and the total duration of the test. Divide the total volume (in gallons) by the total pumping duration (in minutes) to calculate and record the average test pumping rate (in gpm).

VII. Waste Management

Water generated during specific capacity testing will be placed in containers, if required per State or local regulations. Containerized waste will be managed and disposed of properly.

VIII. Data Recording and Management

Data from a specific-capacity test are reduced to a transmissivity estimate for the water-bearing formation surrounding the intake of the tested well. The transmissivity may be estimated using a single-well time-drawdown method with multiple drawdown measurements, or else using a specific-capacity procedure with one drawdown measurement. These options are described below.

Time-Drawdown Method

The time-drawdown method of analyzing transmissivity requires graphical data evaluation, but has several advantages. The method does not require an estimate of the formation storativity and the results are not influenced by well efficiency.

Plot the measured drawdown data (measurements in feet on Y-axis) versus the pumping time (minutes, logarithmic scale on X-axis). The semilog data plot typically shows an abrupt initial drawdown at early time, followed by a straight-line trend of data points. Draw a line through the straight-line trend of data points and extend the line through at least one complete log cycle (e.g., 10 to 100 minutes). The data points need not extend through the entire interval of the drawn line. The drawn line is extended to cover at least one complete log cycle for ease in data analysis. Determine the drawdown change (• s) over one log cycle of time for the line drawdown through the straight-line trend in the data points. The value of transmissivity can be solved using the following equation (Driscoll, 1986):

$$T = 264\, Q \,/\, \triangle\, s,$$

where:

T = transmissivity of the water-bearing zone surrounding the intake of the tested well (gallons per day per foot);

Q = pumping rate during the period of the straight-line trend in data points (gpm); and

$\triangle s$ = drawdown change over one log cycle (ft).

Single Drawdown Measurement Method

This method is relatively easy to use, but it requires an estimate of the formation storativity and the results can be influenced by well efficiency. The transmissivity can be estimated using a single drawdown measurement via the following equation (Walton, 1962):

$$\frac{Q}{s} = \frac{T}{\left[264 \log\left(\frac{Tt}{2{,}693 r_w{}^2 S}\right) - 65.5\right]}$$

Q/s = specific capacity of the well in gpm per foot

Q = average test pumping rate (gpm)

s = drawdown measured inside of tested well after a known duration of pumping (ft)

T = transmissivity of the water-bearing zone surrounding the intake of the tested well (gallons per day per foot)

S = estimated storativity of the aquifer

r_w = effective radius of the well (ft)

t = time between the start of pumping and the time when the drawdown was measured (minutes)

The value of T can be solved iteratively using a specific-capacity test data reduction computer program. If the well screen is surrounded by a sand pack that may be assumed to be substantially more permeable than the formation, the effective radius of the well is taken to be that of the borehole.

The value of S may be estimated without introducing serious error into the results. For confined aquifers, S should be estimated as 0.0001. For unconfined aquifers, the short-term storativity may be comparable to that of a confined aquifer. Only after a protracted pumping duration (several hours or more) does the storativity begin to approximate the aquifer-specific yield of approximately 0.2 to 0.3 (Nwankwor et al., 1984). In the calculation of transmissivity from a specific-capacity test of less than several hours duration, an estimated storativity value of 0.01 can be used.

To obtain an estimate of the K of the water-bearing zone that transmits groundwater to the well, the calculated transmissivity value may be divided by the estimated thickness of the water-bearing zone. In a stratified formation in which the horizontal K may be expected to greatly exceed the vertical K, the thickness of the water-bearing zone may be estimated as the length of the well intake to obtain an estimate of the K immediately surrounding the well intake.

Cautionary Considerations

It should be noted that the above-listed methods are based on the modified non-equilibrium equation. According to Kruseman and de Ridder (1990), these methods are useful provided that:

$$u = \frac{r^2 s}{4Tt}$$

r = effective well radius
S = storativity
T = transmissivity of the test zone (formation interval adjacent to saturated sand pack)
t = the pumping duration

Following data analysis, the value of u should be calculated to confirm that the above condition is satisfied. If u > 0.15, then a different K test method should be employed. These cases are rare when using drawdown data from the pumped well, because the radius is a small number. The S value used in this calculation can be selected on previous site-specific pumping test results using observation well data, or else estimated as described in the previous subsection.

In circumstances when the pumping rate is low (e.g., less than 1 gpm) and the drawdown is high or occurs within the sand pack, the water removed from the well and sand pack storage should be calculated and subtracted from the pumped volume to estimate the volume of water produced by the formation. The volume of water produced by the formation should be divided by the pumping duration to obtain an effective pumping rate for use in calculating T and K.

In situations where the water level in the test well may be influenced by tidal fluctuations, drawdown and recovery data should both be measured and recorded on the same schedule. In these cases, to correct for potential tidal influence, calculate the average magnitude of the drawdown and recovery measured for the same duration during either pumping or drawdown. For example, if the pumping period lasted 30 minutes, calculate the average of the drawdown at 30 minutes and the magnitude of recovery that occurred during the first 30 minutes after shutting off the pump. This average value accounts for the tidal influence assuming that the rate of tidal change was approximately equal during the drawdown and recovery periods, and it should be considered the “effective drawdown” for use in the specific capacity method of Walton (1962). This correction should be useful in many situations, but may not adequately address tidal impacts if the drawdown due to pumping is small compared to the magnitude of the tidal influence. In these cases, it may be necessary to induce more drawdown during the test and/or time the test to coincide with slack tide conditions.

IX. Quality Assurance

QA Quality assurance calculations must be reviewed by a qualified hydrogeologist. Calculations will be provided with backup documentation, such as raw data and graphs of the data.

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Appendix **D**

Slug Test SOP

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SLUG TEST STANDARD OPERATING PROCEDURES

PUMPING TEST PROCEDURES

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A. TEST DESIGN

1. Understand What You Are Testing

An instantaneous change in head (slug) test is conducted in order to determine the hydraulic conductivity/transmissivity of a water-bearing zone in a quick and inexpensive manner. It can be conducted in materials of lower hydraulic conductivity than generally considered suitable for pumping tests. A slug test also does not require disposal of large quantities of water.

However, recognize that a slug test’s shorter time frame and limited stress on the system provides a measurement of hydraulic conductivity on a smaller scale than a pumping test. Because a slug test affects only the aquifer near the well, its results are more strongly influenced by near-well conditions such as the filter pack, poor well development, and skin effects. Therefore, make sure that the stress on the well (i.e., the amount of change in head) is sufficient to test more than the hydraulic conductivity of the filter pack. Although the results of a slug test are not necessarily representative of the average hydraulic conductivity of the area, this limitation does present an opportunity to test discrete layers within an aquifer. Also understand that the storage coefficient (S) usually cannot be determined from a slug test.

2. Slug Test Theory

An estimate of local hydraulic conductivity of the material surrounding a well is calculated by measuring the time/rate of return to static water levels after an instantaneous change in head. Homogeneity and constant aquifer thickness are general assumptions for the test analysis; these are generally met due to the small radius of influence of the test.

Two classes of solutions are generally used: one that assumes water and soil are incompressible (storage is zero; i.e., Bouwer and Rice, and Hvorslev methods), which is a straight-line solution method similar to Thiem; and one that assumes a non-zero storage coefficient (i.e., Cooper et.al, and Hyder et. al methods), which is a type-curve matching solution method similar to Theis.

3. Determine Well Conditions

Unless installed specifically for the test, sound all wells that are to be tested to verify well depth. (Do not use water level meters for this purpose, because some meters have probes that leak and trap water when subjected to excessive pressure.) Verify that the well has been adequately developed, and is not silted in. If the water-level response in the slug test appears to be too sluggish or no response is apparent, the well may need to be redeveloped.

Measure depth to water, or check historic depths to water, to determine if the screen is below the top of water or straddles the piezometric surface. This will determine the types of slug tests (slug-in, slug-out) and mechanisms (water, mechanical, pneumatic) that are applicable for the particular well to be tested. Note that a fully submerged screen is highly preferable for best test results, otherwise a “double-straight line” effect resulting from filter-pack drainage into the well (initial drainage followed by actual aquifer response) will likely be seen in the test response curve (Bower, 1989).

4. Select the Appropriate Slug-Inducing Equipment

A variety of methods are available for inducing a change in water level. The basic requirements are the change needs to take place rapidly (“instantaneous”), and the change needs to be of sufficient magnitude: at least one foot, preferably two to four feet. (Similar results can be achieved with a wide range of induced head change, so a change greater than four feet is not necessary.) The slug can either be introduced (slug in) or withdrawn (slug out). However, if the well screen is open above the water table, slug out is the only method acceptable.

Methods of introducing a slug are as follows:

a) adding clean (DI or potable) water to the well, preferably from a holding vessel with a ball valve that allows the water to drain into the well quickly;
b) dropping a “blank” (typically capped PVC pipe filled with clean sand) into the well; or
c) after raising the water level within a well by applying a vacuum, releasing the vacuum and observing the drop in water level.

Methods of removing a slug are as follows:

a) pulling a slug of water out of the well quickly with a bailer;
b) pulling a “blank” out of the well; or
c) after pressurizing a well and pushing down the water level, releasing pressure from the well and observing the rise in water level.

5. Select the Appropriate Water-Level Measurement Device

Pressure/head changes are rapid (i.e., “instantaneous”), therefore, the measuring device needs to be able to collect measurements quickly and accurately, especially for fast-responding wells. Pressure transducers with dataloggers are best equipped for slug tests. Pressure transducers are also necessary for closed wells in which water level changes are induced by pressure or vacuum.

(a) Pressure Transducers and Data Logger Combination

Transducers connected to electronic data loggers provide rapid water-level measurements with accuracy and ease. Some electronic data loggers (i.e., Hermit) collect and store data from a number of input channels (downhole pressure transducers plus atmospheric pressure) to provide water-level measurements in multiple within several hundred feet radius of the data logger, while others consist of a single logging transducer (i.e., Troll™, Levelogger™). Typical loggers take readings at preprogrammed linear or logarithmic intervals. If desired, data can be transferred to a personal computer for processing.

Small-diameter transducers (typically 0.5 to 0.75 in) are available that cover a range of pressures. Because they yield readings accurate to a percentage of their pressure range (usually about ±0.1 percent of the range in the center of that range, and ±0.2 percent near the limits) transducers that span a wide pressure range have lower absolute accuracies than those that span a narrow range. For example, a typical transducer with a 5 psi range detects water-level changes over a 11.6 ft with an accuracy of ±0.01 ft, whereas, a transducer with a 15 psi range detects changes over a 34.7 ft with an accuracy of ±0.03 ft. Thus, to ensure the greatest accuracy, select the transducer with the pressure range that most closely encompasses the anticipated drawdown or water-level change. Install the transducer at a depth at least 2 feet from the bottom of the well, but below the targeted drawdown estimated for the well.

Caution: To prevent transducer malfunction, do not submerge transducers in excess of their operating range.

(b) Water Level Meters, Interface Probes

These devices provide quick and easy water-level measurements with reasonable accuracy. They employ a sensor that is lowered into a well on the end of a marked cable (typically imprinted in feet and hundredths of a foot). When the sensor contacts water, a circuit is completed, activating a light, audio signal, ammeter, or digital display in the cable reel or housing. However, because the measurements are manual, the speed of readings cannot match those of a pressure transducer with a data logger. Thus, a water level meter is most useful with slow-responding wells, typically installed in low-permeability formations.

6. Verify Measuring Device Accuracy

Test pressure transducers and data logger readings using a bucket or barrel filled with water. Submerge each transducer, accurately measure the water head above the transducer, and compare the measurement to the data-logger reading. Check transducer response to changing heads by raising the transducer a certain distance, observing the change in the datalogger reading, and then measuring the distance with a standard steel tape. Water level meters should be in good working condition and calibrated, ensuring there are no breaks or splices in the cable.

7. Plan for Test Well Water Disposal

If the water quality is such that direct discharge to the ground is not permitted, arrange for collection and disposal for standard slug-out testing. Discharge water must be disposed according to all applicable laws and regu1ations. Contact the governing agencies to determine which restrictions apply. ARCADIS should not be responsible for signing manifests and should not "take possession" of discharged water.

B. PRETEST ACTIVITIES

1. Establish a Reference Point for Measuring Water Levels

At each test well, establish and clearly mark the position of the selected reference point (often the north side, top of the casing). Determine the elevation of this point, record it, and state how this elevation was determined. This elevation point is important to establish the position of the piezometric surface, so it must be determined accurately.

2. Record Background Water Levels

Measure the groundwater level in the test well before beginning the test for a period of time equal to the length of the slug test response. This will help detect any background water level fluctuations and establish a reference static water level. Be sure to allow time for equilibration with atmospheric pressure for wells with unvented caps. If possible, arrange to have nearby active wells shut down or pumped at a constant rate to ease data interpretation.

3. Set-up: Decontamination

Make sure all equipment that enters the test well (slug, water-level meter, transducer) is decontaminated before use. If testing multiple wells, start with the least contaminated progressing to the most contaminated.

4. Set-up: Remaining Equipment Required for Test

Keep sensitive electronic equipment away from devices that generate significant magnetic fields. For example, do not place data loggers near electric power generators or electric pump motors. Likewise, radio signals may cause dataloggers or computers to malfunction. Secure data logger and transducer cables at the well head to prevent movement that would affect measurements. Mark a reference point on transducer cables and check regularly to detect slippage.

5. Perform a Job Safety Analysis

To ensure that everyone is aware of the hazards associated with the work, and that each person knows his/her responsibilities during the preliminary and full-scale test, run through a JSA of the test before the start of pumping.

C. CONDUCTING THE TEST

1. Record Information

(a) Use appropriate data forms
(b) Record all required background information, including well geometry, on logs before beginning the test
(c) Record time as military (24-hour) time
(d) Record the initial depth to water with a water-level meter. (This can be entered into the datalogger if one is being used.)

2. Start the Test

(a) Introduce or remove the slug quickly, causing a measurable change in water level.
(b) Measure water-level response to the initial change at closely spaced intervals (preferably 0.5 second or less to catch fast response) in order to define the water-level response curve.
(c) Continue measuring and recording depth-time measurements until the

water level has equilibrated or a clear trend on a semi-log plot of time versus depth has been established. Measurements taken manually should continue until the water level has recovered about 80%.

3. Reverse Test

If desired, after a slug-in test has been finished and equilibrium reached, a slug-out test can be performed as a check.

4. Post-test Procedure

Make a preliminary analysis of the data before leaving the test area. Compare volume of slug to actual water displacement in the well. Evaluate the quality of the data, and the method of analysis applicable for the results. If a clear trend was not established, the test may need to be re-run. Ensure that equilibrium has been reached before re-running a test in the same well.

D. ASSESSING TEST RESULTS

1. Have Pertinent Well Construction Details

To evaluate data from the test, it will be necessary to have well construction information, such as the following:

- Lithologic logs
- Well depths
- Screen lengths
- Filter pack thickness and length
- Test well casing radius
- Borehole radius
- Sand pack grain size (affects the size of the practical borehole radius)
- Thickness of saturated zone
- Initial water depth
- Initial head change from slug

2. Determine the Type of Response to the Test

The type of response to the test is as important as the type of permeable zone (confined, unconfined) for picking the type of analysis. As with pumping tests, do not assume that all standard analyses (Bower and Rice; Hvorslev; Cooper, Bredehoeft, Papadopulos) are suitable; pick the type of analysis based on the goodness-of-fit of the response (Herzog and Morse, 1990) to the theoretical curve. Do not force the data; if a clear straight line does not exist then the standard straight-line analytical methods may not be appropriate.

Wells testing confined aquifers with a high transmissivity or long water column (large water mass within the casing) can show an oscillatory recovery (underdamped or critically damped; see ASTM D5785 and ASTM D5881) to initial water level; common response is an exponential decay (overdamped response, frictional forces within the aquifer are dominant over inertial; see ASTM D4104 and ASTM D5912). These oscillatory test results require calculation of the angular frequency and damping factor (Kipp, 1985; van der Kamp, 1976) to account for the inertial effects before solving for transmissivity. The underdamped solution technique is available in the standard aquifer test program, AQTESOLV, and in public domain spreadsheet programs available from the USGS (http://pubs.usgs.gov/of/2002/ofr02197/) and from the Kansas Geological Survey (http:www.kgs.ku.edu/Hydro/Publications/OFR00_40/High_K.zip).

Note: the critically damped well response is a transitional response (showing oscillations) between overdamped and underdamped; its analysis requires the type-curve matching method by Kipp (1985). It is determined by a dimensionless "damping factor":

$$\zeta = \frac{\alpha\left(\sigma + {}^{1}\!/_{4}\,\ln\beta\right)}{2\beta^{1/2}}$$

where $\zeta > 1$ is overdamped; $\zeta = 1$ is critically damped; and $\zeta < 1$ is underdamped.

3. Decontaminate All Equipment Contacting Site Groundwater and Soil

Use appropriate decontamination procedures before proceeding to the next well and/or leaving the site.

E. SPECIAL CONSIDERATIONS

1. Wells Containing Floating Nonaqueous Phase Liquids

It is best to use pressure transducers to measure water levels in wells containing floating product such as gasoline. Contact with floating product, however, may make transducers and cable unsuitable for future use. Thus, protect each transducer and cable assembly by encasing it in plastic tubing or pipe. Be sure that each protected transducer still can respond accurately to any pressure changes.

As an alternative to pressure transducers, make manual measurements (using an interface probe) of both the fuel level and water level individually. Then correct the observed thickness of floating product by its density to arrive at the effective water level. This manual procedure will work, but takes time and is only suitable for slow-responding wells.

2. Karst and Cavernous Aquifers

Recognize that the response of the slug tests within a Karst regime will be as diverse as the stratigraphy. Document the well stratigraphy to understand the range in responses measured within a single groundwater zone.

3. Fractured Aquifers

The upper boundary condition for the Bower-Rice and Hvorslev methods, based on the Thiem analysis, is a no-flow boundary. Often, the residuum above fractured aquifers are at least partially saturated and serve as a leaky upper boundary; this condition cannot generally be confirmed by slug tests.

Fractured-zone aquifers typically meet the assumptions of the analysis by Cooper-Bredehoeft-Papadopulos, although care should be taken in the interpretation in case the screened zone may cross a single fracture or discrete zone

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Appendix **E**

Long-Term Pumping Test SOP

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PUMPING TEST
STANDARD OPERATING PROCEUDRES

Rev. #: 01

Rev Date: September 2008

Approval Signatures

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Prepared by: ______________________ Date: September 29, 2008

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Reviewed by: ______________________ Date: September 29, 2008
(Technical Expert)

I. Test Design

In general conventional hydraulic testing is conducted to provide answers to questions related to water supply problems. Tests are conducted over longer periods of time and provide estimates of hydraulic conductivity values averaged over large aquifer volumes. These tests tend to underestimate the highest hydraulic conductivity values and overestimate the lowest.

When conducting tests for remediation hydrogeology purposes it is important to indentify aquifer heterogeneities which ultimately control the transport of contaminants and reagents distribution within the aquifer. Short-term tests may help identify particular depositional elements and hydraulic conductivity trends and variability associated with facies changes in the aquifer. Data collected from short-term test can then be correlated with detailed hydrostratigraphic information to assist in the development of conceptual site models that describe the transport of contaminants and distribution of reagents.

1. Understand Aquifer Conditions

An aquifer (or permeable zone) pumping test is conducted in order to determine the hydraulic properties (transmissivity, hydraulic conductivity, storage coefficient, leakage, boundaries, anisotropy) of a water-bearing zone or system (including confining beds). Proper design of a pumping test requires a general understanding of the potential hydrologic system prior to the test, so that suitable data are collected to evaluate system parameters. The designer of the test must first develop an appropriate set of assumptions (conceptual model), either taken from previous tests in the immediate area or from well logs and an assessment of the site features that can affect the test (soil or rock types, depth to water, surface- water bodies, existing wells, storm drains). This conceptual model will then help the designer anticipate the necessary design factors such as: number of wells, depth and placement of wells; pumping rate(s); frequency of water-level measurements; and length of pumping. These factors will help the designer determine from the test results the effects of recharge and restrictive boundaries, aquifer geometry, secondary porosity effects (fractures, solution channels), the nature and extent of potentially confining layers, and aquifer interconnections.

2. Estimate Aquifer Parameters

Although the objective of a pumping test is to determine the principal aquifer parameters, the conceptual model requires a prediction of some of these parameters for the design process (i.e., observation well number and spacing requires approximate transmissivity and storage coefficient values). Hydraulic conductivity may be estimated from textural or hydraulic testing of aquifer materials in the laboratory, or from data collected and observations made during drilling or well development (see Driscoll, 1986). Considerable experience is needed to apply these methods for anything but preliminary estimating purposes. Therefore, use as many approaches as possible when making these estimates and remember that they are only estimates. Be ready to adjust preliminary estimates as more information becomes available throughout the process.

For larger tests (and thus larger pumping wells), potential casing storage effects and well (friction and formation) loss may need to be calculated prior to the test. Also, optimum pump size may need to be calculated. These will require an estimate of specific capacity, which is the well discharge rate per unit of drawdown measured at a given time. Specific capacity is typically determined from a step-drawdown test. An added benefit to conducting a step-drawdown test is the graphical results can also be used to calculate transmissivity (but not storage coefficient) in addition to well losses (see Section B.9).

3. Locate the Pumped Well

At many sites, the pumping well location is predetermined because an existing well suits the needs of the test, or the hydraulic properties of a specific location must be measured. If the pumping well location can be selected with relative freedom, the following criteria can be used as a guide for its installation:

a) where the hydrogeology represents the area of interest;

b) proximity to existing wells that could be used as observation wells (see guidelines 5, 6 and 7 below);

c) within the targeted contaminant plume whenever possible;

d) outside the contaminant plume if the system is areally homogeneous (or nearly so) and pumping of contaminated water poses an insurmountable problem;

e) away from groundwater system boundaries (assuming their approximate position is known) when the test purpose is solely to measure aquifer storage and transmission properties;

f) close to groundwater system boundaries (assuming their approximate position is known) when requiring boundary location, orientation (both positive and negative boundaries), or degree of connection (positive boundaries);

g) away from surface features that could obscure the data (for example, surface-water bodies) and away from areas subject to heavy-equipment traffic (i.e., railways and highways) that would put unpredictable stress on the aquifer, unless desiring specific information about the interrelationship of the groundwater system and surface features;

h) away from other producing wells that may not be shut down and may affect test data; and

i) where the site is safely and easily accessible to equipment and personnel.

Although these guidelines generally support test success, strictly adhering to them may produce conflicting test designs. Resolving these design conflicts requires good judgment based on a clear understanding of the test priorities and an appropriate knowledge of the local groundwater system.

4. Design the Pumped Well

a) The casing must accommodate the pump used for the test and allow ample additional space for measuring equipment.

b) The pumped well should be as efficient as possible through sound drilling practices, installation, and construction. A wire-wrapped screen and site-specific filter pack, designed from a sieve analysis, should be used to reduce factors that will mask true aquifer response.

c) If possible, a stilling pipe should be installed in the pumped well for making water- level measurements. The stilling pipe will dampen water-level fluctuations caused by pump vibration, eliminate measurement errors associated with cascading water, and isolate pressure transducers from pressure transients near the pump intake.

d) Generally, the screen in the pumped well should fully penetrate the tested zone to eliminate the complicated data analysis and interpretation required to correct for partial penetration effects (induced vertical flow component in addition to radial flow), with the following two exceptions:

   1) if the screen would form a conduit capable of transmitting chemicals from a contaminated horizon to a clean horizon; or

   2) when attempting to determine an aquifer's vertical anisotropy (ratio of vertical to horizontal hydraulic conductivity). This determination is necessary if remediation well capture zones will not affect the full thickness of the aquifer.

For these two conditions, the pumped well should only penetrate the contaminated portion of the aquifer. In addition, cost considerations may limit full penetration of the tested zone.

e) The pumped well must be fully developed to maximize the pumping rate from wells with limited available drawdown, simplify data interpretation and assure that no additional development occurs during the test.

f) Often, pumping wells are later used as monitoring or recovery wells. Such wells should be designed according to the requirements of the particular application without compromising the aforementioned standards for pumped wells.

5. Determine the Number of Observation Wells

Observation wells help quantify the size, shape, position, and rate of change of the cone of depression formed by pumping, making it possible to determine aquifer parameters. Adding wells increases the amount and accuracy of information acquired, and improves confidence in the data. The number of observation wells selected, however, must balance the information needs with the cost of constructing them.

Without observation wells, only transient analysis (time-drawdown) methods may be used to determine aquifer properties, and only transmissivity and hydraulic conductivity can be determined. A single observation well makes it possible to determine storage coefficient, but data analysis is still restricted to transient methods. Two or more observation wells permit the use of distance-drawdown methods of analysis, greatly improving the accuracy of aquifer parameter estimates. Distance-drawdown analysis is especially important whenever transient analysis methods are apt to produce erroneous results, as often occurs in unconfined aquifers, tight sediments, leaky aquifers, and aquifers with boundaries near the pumped well. Therefore, when possible, use at least two observation wells during a pumping test. Determining parameters such as leakage/delayed yield and anisotropy usually require more than two observation wells.

6. Design the Observation Wells

a) The observation well diameter must be large enough to accommodate instrumentation used to measure water levels and small enough that the volume of water in the well does not cause a time lag in responding to aquifer drawdown changes.

b) Unlike the pumped well, observation wells need not be highly efficient, just open enough to reflect pressure changes that occur in the aquifer. Thus, inexpensive construction materials such as slotted screens may be used (unless they will be used later as monitoring, recovery, or injection wells). Yet, to accurately represent the potentiometric changes that may differ vertically in the aquifer, the well intake must be open to the aquifer from top to bottom. This objective can be achieved with moderate well development. Techniques such as surging and bailing, which provide modestly effective development, can be used.

c) Generally, observation well screens should be fully penetrating to eliminate complications in data interpretation caused by partial penetration. As with the pumping well, the exceptions to this rule are:

    1) Avoid fully penetrating screens where they would create a conduit capable of spreading contamination;

2) Use short screens to assess vertical anisotropy at discrete elevations in the aquifer.

Short screens are appropriate for observation wells installed in aquitards that are being used to assess connectivity, recharge, or delayed yield factors.

As stated above, fully penetrating wells will simplify the data analysis because hydraulic theory for fully penetrating systems is simpler than that for partially penetrating ones. Theory also predicts that, for a confined aquifer, an observation well will show fully penetrating response if either it or the pumped well is fully penetrating. That is, in theory, both need not be fully penetrating --it is sufficient that just one or the other be fully penetrating to observe the simplified fully-penetrating response. In practice, however, it is preferable that both the pumped well and the observation well be fully penetrating, if possible. In aquifers where hydraulic conductivity varies substantially with depth, it is possible that a fully penetrating response would not actually occur unless both the pumped well and observation well were fully penetrating.

7. Situate the Observation Wells

a) Lateral Distribution

When using two observation wells, they should be positioned along a straight line radiating from the well. Accurately assessing horizontal anisotropy or near-well boundaries requires three pairs or sets of observation wells positioned along three different lines emanating from the well. If the principal axis of anisotropy is known, two sets of observation wells will suffice, one along the principal direction of anisotropy and one perpendicular to it. For example, if a fractured rock aquifer is known to be more permeable north-south than east-west, one set of two or more observation wells would be installed on a line north (or south) of the pumped well and another set along a line east (or west) of the pumped well.

In theory, single wells placed on three different lines emanating from the pumped well are sufficient to assess horizontal anisotropy. In practice, however, other heterogeneities can influence drawdown readings enough to bias the calculated anisotropy if just a single well is used along each line. Therefore, it is preferable to use pairs of wells whenever possible.

b) Well Spacing

Observation wells along a particular line from the pumped well should be spaced logarithmically with the distance to each successive observation well approximately double that to the preceding well. For example, three observation wells may be placed at distances of 10 ft, 20 ft, and 40 ft from the pumped well, or 50 ft, 100 ft, and 200 ft from the pumped well.

There are advantages and disadvantages to locating observation wells either near to, or far from, the pumped well. Distance drawdown analysis methods tend to integrate aquifer properties over the area spanned by the observation wells, so distant wells tend to yield aquifer parameters representative of a broad area of aquifer. At great distances, however, wells may exhibit drawdowns so small that they are difficult to measure accurately or analyze confidently. On the other hand, observation wells installed near the pumped well show more substantial drawdown but tend to reveal aquifer properties on a smaller scale. Situating observation wells, therefore, depends on the type of information required. For contamination investigations of small plumes, closely spaced observation wells provide satisfactory data.

The data set will be more reliable if substantial drawdowns can be attained in the observation wells. This is accomplished by maximizing the flow rate and locating the observation wells sufficiently close to the pumped well. As a rule of thumb, the distance from the pumped well to the nearest observation well should not exceed the square root of the expected radius of influence of the pumped well. R can be determined from:

$$R = \sqrt{\frac{0.04Tt}{S}}$$

where

R = radius of influence in ft

T = estimated transmissivity in ft^2/day

t = pumping test duration in days

S = storage coefficient

For example, in tight sediments, if the expected radius of influence is less than 100 ft, at least one observation well should be located within 10ft of the pumped well.

Be aware that the oft-repeated recommendation to locate the nearest observation well one or two aquifer thicknesses from the pumped well is actually a generalization (not entirely correct) for locating partially-penetrating observation wells away from a partially-penetrating pumping well. The actual radial distance for a partially-penetrating observation well must take into account anisotropy, as follows:

$$r = \frac{1.5b}{\sqrt{\frac{K_z}{K_{xy}}}}$$

where

r = radius from pumping well

b = thickness of aquifer

K_z = vertical hydraulic conductivity

K_{xy} = horizontal hydraulic conductivity

In most instances, and especially in unconfined or tight sediments, use closely spaced observation wells and eliminate partial penetration effects by using fully penetrating wells, or compensate for partial penetration effects by determining the anisotropy of the aquifer.

c) Vertical Distribution of Observation Wells

Generally, make sure that observation well screens are located in the pumped aquifer and fully penetrate it. To determine vertical anisotropy, however, screens must only partially penetrate the aquifer. For this determination, install observation wells in pairs at the same location, with one well screened in the pumped interval and the other screened in an unpumped interval of the aquifer to get a three-dimensional view of the pressure reductions caused by pumping.

If pumping is expected to induce leakage across an aquitard and if the leakance must be determined, place one or two piezometers in the aquitard to assess the magnitude of the drawdown, if any, created by the pumped well. Aquitard-monitoring wells should have short screens approximately centered in the aquitard, to keep the screen as far as possible from the top and bottom of the aquitard. Ideally, an aquitard observation well should be drilled at the same location as an observation well completed in the pumped aquifer.

8. Establish the Pumping Test Duration

a) The duration of pumping tests can range from a few hours to a few weeks depending upon the nature of the formation and the type of information required. For example, in highly transmissive confined sediments, if only near-well transmissivity must be known, a 2-hour test might suffice. However, to acquire information about boundaries or leakage, or if sediments are tight or unconfined, a much longer test is required. The preliminary test of the pumped well (Section B.9) will help in planning the test length.

b) For confined aquifers, a test duration of 24 to 48 hours will generally provide the information required.

c) Longer tests are required for unconfined aquifers because the cone of depression expands more slowly and delayed-drainage effects retard the response of the aquifer to pumping. Plan to conduct pumping tests in unconfined aquifers for 3 days or longer.

d) If leakage effects among aquifers must be determined, a longer test is appropriate. For example, under confined conditions, it may be desirable to extend the test to two or three days.

e) Economics may dictate curtailing the length of the pumping test if treating or storing pumped water is expensive. If water disposal is inexpensive, however, it makes sense to extend the test because the cost of the additional pumping and monitoring required is generally nominal.

9. Select the Appropriate Flow Rate and Measurement Device

a) The objective of the pumping test is to stress the aquifer sufficiently to obtain a meaningful, measurable response. Generally, the magnitude of the drawdown response in most observation wells is small. Thus, in most aquifer tests, design the well and pump intake in such a way that a sufficient stress is placed on the aquifer system that can be measured at a distance.

b) Select the pumping rate on the basis of a preliminary test (such as a step-drawdown test, Section B.9) so that the rate can be sustained by the pump for the duration of the test. The rate should not be so large that the water level is drawn down into the screen area, causing cascading effects and entrained air; under no circumstances should the water level be drawn down to the water entry of the pump or tail pipe.

c) Small variations in the discharge rate create large errors in the calculation of aquifer parameters. Therefore, sustaining a constant discharge rate is more important than knowing the exact rate with great accuracy. Accordingly, maintain the flow rate as closely as practical to a constant value, usually within ±1 percent or less. This can be achieved only if the flow rate can be measured precisely and adjusted easily as needed.

d) Always operate the pump against a partially closed valve so that, as drawdown increases during the test, a compensating reduction in back pressure is achieved by gradually opening the valve. The correct valve and flow measurement method are critical to this requirement. Select a valve that can be opened or closed in tiny increments to ease flow-rate control. A ball valve that opens fully or closes fully with a single 90-degree turn of a handle is undesirable because careful adjustments are difficult to achieve. A better choice is a gate valve that requires several 360-degree turns to open or close.

e) Flow measurement devices are typically based on three principles; head-type (orifice, venturi), velocity-type (magnetic, ultrasonic), and displacement-type (rotor, paddlewheel). Measurement devices/methods for a pumping test, in order of preference, are as follows:

  1) Orifice weir with manometer (see Driscoll, pg 537): This is the best method of measuring the flow rate because it is precise, allows instantaneous reading of the flow rate so that adjustments can be made readily, and is relatively “low-tech”. While most orifice weirs accommodate higher flow rates, small-scale versions can be made for flows as small as a few gallons per minute. Such custom-made meters can be calibrated easily in the field with a bucket and stop watch. Installing a totalizing meter in line with and upstream from the orifice weir provides assurance that the total discharge for the test is calculated accurately. After completing the test, total discharge volume is divided by test duration to determine average flow rate.

  2) Instantaneous (ultrasonic) flow meter: non-invasive, can be equipped with a data logger. Some meters may not respond properly when pumping sediment-laden water or two-phase fluids like hydrocarbons and water.

  3) Paddlewheel totalizing meter: shows total volume pumped. When using this type of meter, flow rate must be determined by taking consecutive readings and dividing by the time between them. Accuracy may vary from one meter to another. Also may not respond properly when pumping sediment-laden water or two-phase fluids. Meter inaccuracy at low flow rates can be allayed by installing a flow restrictor (such as manufactured by Clack Corporation) upstream of the meter. The restrictor creates enough back pressure on the pumping unit to minimize flow rate fluctuations.

  4) Bucket, or other container of known volume, and stop watch. For low flows, this procedure is about as accurate as any for determining the flow rate. It also serves as a reliable calibration tool for other flow measurement devices.

Other methods of measuring flow rate involve using various types of weirs, flumes, and open-discharge pipes generally do not provide the precision required for controlling the flow rate during a constant-rate pumping test.

10. Select the Pump

a) The pump used must have sufficient capacity to maintain the required discharge throughout the constant-rate portion of the test and to produce the various flow rates required for the step-drawdown test.

b) The pump should be capable of delivering the planned discharge rate at pressures substantially higher than the apparent nominal pressure required to lift water to the surface and overcome friction losses in the piping system. Pumping against a high head such as 60 to 100 psi tends to reduce discharge rate variations. It also permits operating the pump against a partially closed valve, creating additional head to help minimize flow-rate fluctuations during the test.

c) Submersible or turbine pumps driven by electric motors are ideal for conducting pumping tests because (barring spikes or storms) they run at nearly constant rates, producing generally uniform flow. Turbine pumps driven by gasoline or diesel engines, however, cause greater flow-rate variations because engine output can vary with fuel mixture, and air temperature and pressure.

d) The pump should be equipped with a check valve so that water in the column pipe and discharge pipes doesn't siphon back into the well following pump shut off. This prevents a sudden charge of water from obscuring the early recovery data and making analysis more difficult.

11. Plan for Pumped Water Disposal

a) Discharge pumped water so that pumped aquifer zones are not recharged. To accomplish this, pipe water to nearby storm or sanitary sewers, or lined surface-water bodies. If these options are not available, arrange to spread the discharge water on the ground sufficiently far from the pumping test site so that infiltration will not affect the test results.

b) If the water quality is such that direct discharge is not permitted, treatment may be necessary. Occasionally, water treatment facilities are already available on site. Alternatively, it may be possible to arrange for temporary treatment equipment just for the pumping test. If disposal during the test is not possible, the fluid can be discharged to containers such as frac tanks temporarily. Provisions must be made for the appropriate number and size of containers to handle the volume of water pumped during well development, step-drawdown testing, and constant-rate testing, plus a safety margin.

c) Discharge water must be disposed according to all applicable laws and regu1ations. Contact the governing agencies to determine which restrictions apply.

d) ARCADIS should not be responsible for signing manifests and should not "take possession" of discharged water.

12. Check for Casing Storage

Casing storage effects will render useless the early time/drawdown data from pumping tests. The larger the well diameter and the lower the specific capacity, the longer casing storage effects persist. Data recorded before casing storage effects end (at t_c) cannot be analyzed by any method.

The duration of the casing-storage affected portion of the test can be estimated as follows:

$$t_c = \frac{0.6\left(D^2 - d^2\right)}{Q/s}$$

where

t_c = duration of casing storage effect (‘critical time’), in minutes

D = inside diameter of well casing, in inches

d = outside diameter of pump column pipe, in inches

Q = flow rate, in gpm

s = expected drawdown in the pumped well, in ft

Before conducting the test, it is important to estimate t_c. If the value is large, take steps to minimize storage effects if possible. For example, a packer may be installed with the pump column pipe to keep the water standing in the well casing from being removed from the well. If this is done, the packer must be specially designed to permit measurement of the hydraulic pressure in the well just under the packer. Alternatively, it may be possible to install ballast material alongside the column pipe to take up space and reduce the volume of water stored in the casing. For example, a 3.5-inch OD PVC pipe run alongside the column pipe in a low-yielding, 4-inch well, can reduce the duration of casing storage effects by 75 percent.

To demonstrate the significance of casing storage, a 4-inch test well in tight sediments with 1.25-inch column pipe producing 2 gpm with 30 ft of drawdown results in the following calculation:

$$t_c = \frac{0.6\left(4.026^2 - 1.66^2\right)}{2/30}$$

= 121 minutes

Thus, the first two hours of test data from this well cannot be analyzed.

In filter-packed wells, if water in the filter pack can drain quickly into the well (such as in wells that are screened across the water table), the equation for $\boldsymbol{t_c}$ must be modified to account for filter pack storage. The accomplish this, the term

$$D^2 - d^2$$

is replaced by

$$\left(D^2 - d^2\right) + S_y\left(B_d{}^2 - C_d{}^2\right)$$

where

B_d = diameter of borehole, in inches

C_d = outside diameter of casing, in inches

S_y = short-term specific yield of filter pack material --approximately 0.1 or 0.15

II. Pretest Activities

a) Unless installed specifically for the test, sound all wells for use in the test to verify well depth. (Do not use water level meters for this purpose, because some meters have probes that leak and trap water when subjected to excessive pressure.) Also, if adequate connection to the aquifer is suspect, conduct a slug test (either ‘in’ or ‘out’ - attempt to change the water level by at least 2 feet) in the observation wells. If the water-level response is too sluggish or no response is apparent, redevelop the well.

b) Label all wells (temporarily, if necessary) for quick and easy identification throughout the test.

c) Unless previously verified, measure the distance of all observation wells from the pumping well to the nearest foot.

2. Select Appropriate Water Level Measuring Devices

a) Pressure Transducers and Data Logger Combination

Transducers connected to electronic data loggers provide rapid water-level measurements with accuracy and ease. Some electronic data loggers (i.e., Hermit) collect and store data from a number of input channels (downhole pressure transducers plus atmospheric pressure) to provide water-level measurements in multiple within several hundred feet radius of the data logger, while others consist of a single logging transducer (i.e., Troll™, Levelogger™). Typical loggers take readings at preprogrammed linear or logarithmic intervals. If desired, data can be transferred to a personal computer for processing.

Small-diameter transducers (typically 0.5 to 0.75 in) are available that cover a range of pressures. Because they yield readings accurate to a percentage of their pressure range (usually about ±0.1 percent of the range in the center of that range, and ±0.2 percent near the limits) transducers that span a wide pressure range have lower absolute accuracies than those that span a narrow range. For example, a typical transducer with a 5 psi range detects water-level changes over a 11.6 ft with an accuracy of ±0.01 ft, whereas, a transducer with a 15 psi range detects changes over a 34.7 ft with an accuracy of ±0.03 ft. Thus, to ensure the greatest accuracy, select the transducer with the pressure range that most closely encompasses the anticipated drawdown or water-level change. Furthermore, confirm transducer water-level measurements throughout a test by manually taking regular water-level readings with a water level meter.

Caution: To prevent transducer malfunction, do not submerge transducers in excess of their operating range.

b) Water Level Meters, Interface Probes

These devices provide quick and easy water-level measurements with reasonable accuracy. They employ a sensor that is lowered into a well on the end of a marked cable (typically imprinted in feet and hundredths of a foot). When the sensor contacts water, a circuit is completed, activating a light, audio signal, ammeter, or digital display in the cable reel or housing. However, because the measurements are manual, the speed of readings cannot match those of a pressure transducer with a data logger. Thus, a water level meter is most useful in taking correlative, manual measurements in wells as a backup and for data checking, as well as measuring wells outside the active observation well network.

When appropriate, one water level meter should be used to take readings in all wells. If more than one meter is used to make site-wide water-level measurements, record the serial numbers and make comparison measurements within a single well to calibrate to a common standard.

c) Wetted Steel Tape

When using a steel tape, attach a weight to the bottom, wipe dry and coat the lower 2 to 3 feet with carpenter's chalk or water-soluble ink from a felt-tip marker, lower the tape into the well until part of the coated section extends below the water level, hold one of the major division (e.g., foot) markings at the predetermined measuring point, and record this reading. After withdrawal, read the wetted line on the coated section to the nearest 0.01 ft. Subtract this reading from the mark held at the measuring point; the difference is the actual depth to water.

A wetted steel tape is accurate and reliable, and is useful to verify and calibrate readings from other instruments. The procedure, however, is more time-consuming than others, limiting its usefulness during the early portion of pumping test when many rapid measurements are required. Furthermore, the approximate depth to water must be known in advance to ensure that part of the chalked section is submerged to produce the wetted line.

3. Verify Measuring Device Accuracy

Test pressure transducers and data logger readings using a bucket or barrel filled with water. Submerge each transducer, accurately measure the water head above the transducer, and compare the measurement to the data-logger reading. Check transducer response to changing heads by raising the transducer a certain distance, observing the change in the datalogger reading, and then measuring the distance with a standard steel tape. Water level meters should be in good working condition and calibrated, ensuring there are no breaks or splices in the cable.

4. Establish a Reference Point for Measuring Water Levels

At each well, establish and clearly mark the position of the selected reference point (often the north side, top of the casing). Determine the elevation of this point, record it, and state how this elevation was determined. This elevation point is important to establish the position of the piezometric surface, so it must be determined accurately.

5. Record Background Water Levels

To establish local trends, measure groundwater levels in all test wells and on-site surface water levels at regular intervals for several days before pumping any of the test wells. Although two days preceding the test may be enough (this meets the standards of some regulators), ideally the period of time should be at least equal to the length of the pumping test (three days to a week is optimum). Unless extreme variations are expected, such as significantly increased stream discharge in response to off-site precipitation, only surface water bodies within the radius of influence of the pumping well need to be monitored. A well outside the radius of influence may provide valuable information about water-level trends if monitored before, during, and after the pumping test. In areas that could be influenced by tidal fluctuations, collect information regarding local tidal variations before, during, and after the test.

If levels in the zones to be monitored during the test might be affected by pumping of other nearby wells, gather information about the discharge rates and operating times of those wells. Also, monitor water levels for a sufficient period before the test to evaluate the influence of nearby wells. Water-level monitoring should be done far enough in advance to allow time to negotiate with well owners and take appropriate action. If possible, arrange to have nearby wells shut down or pumped at a constant rate to ease data interpretation.

6. Record Barometric Pressure

Atmospheric-pressure changes can cause water level changes in confined or semi-confined aquifers, leading to erroneous conclusions about aquifer parameters. To correct for these changes, the barometric efficiency of each appropriate aquifer must be determined. Aquifer barometric efficiency (BE), a ratio of aquifer head change to atmospheric pressure change, can be calculated using:

$$BE = \left(\frac{\Delta h}{\Delta B_p} \right) 100\,\%$$

where

BE = barometric efficiency, in percent

Δh = change in water level resulting from change in atmospheric pressure, in feet

ΔB_p, = change in atmospheric pressure, in feet of water

To measure atmospheric pressure changes, either ensure that the dataloggers being used also measure barometric pressure, or obtain data from a nearby source. Barometric pressure must be recorded throughout the background water-level-measurement period and throughout the test. Ideally, barometric pressure and water-level measurements should be made during a time of significant atmospheric pressure change so their relationship can be more easily correlated.

Logging transducers with vented cables (e.g.: Troll, miniTroll) already account for barometric pressure and no additional adjustment is required.

7. Install a Rain Gauge

Heavy precipitation can cause a significant water-table rise in shallow aquifers. Note that rainfall data from nearby weather stations or airports may not be representative, because precipitation patterns may vary greatly over short distances. Therefore, when testing shallow aquifers, a rain gauge should be installed at the test site and monitored during rainfall. Keep in mind that storm sewers can channel large volumes of water rapidly to shallow aquifers.

8. Set-up: Remaining Equipment Required for Test

a) Keep sensitive electronic equipment away from devices that generate significant magnetic fields. For example, do not place data loggers near electric power generators or electric pump motors. Likewise, radio signals may cause dataloggers or computers to malfunction.

b) Secure data logger and transducer cables at the well head to prevent movement that would affect measurements. Mark a reference point on transducer cables and check regularly to detect slippage.

c) Provide adequate lighting for night readings.

d) Identify all equipment to be used in the test that will affect data. For example, describe (by serial number or otherwise) the pump, any isolation packers, water level meters, data loggers, rain gauges, barometers, flow meters, buckets or volumetric containers, watches, and steel tapes used.

e) Consider having backups for key equipment such as data loggers, generators, water level meters, etc.

9. Perform a Job Safety Analysis

To ensure that everyone is aware of the hazards associated with the work, and that each person knows his/her responsibilities during the preliminary and full-scale test, run through a JSA of the test before the start of pumping.

10. Conduct a Preliminary Pumping (Step-Drawdown) Test

Conduct a short-term preliminary test of the pumping well to estimate the hydraulic properties of the aquifer, estimate the duration of the test, and establish a pumping rate. A step-drawdown test is the most efficient preliminary test to use. If other constraints determine flow rate and the flow rate is sustainable, a step test is unnecessary.

The concept of step-drawdown testing in wells was first developed by Jacob (1947). He proposed that drawdown in a well has two components: formation loss (laminar, proportional to the discharge), and well loss (turbulent, proportional approximately to the square of the discharge). Jacob outlined a multiple-step drawdown test where discharge was increased at specific times, as if pumping of the well was held constant and additional wells were introduced at corresponding increases in pumping rates. Rorbaugh (1953) later noted that Jacob’s assumption of second-order turbulent flow did not take into account that turbulence at low rates of discharge is not fully developed. Thus the exponent for turbulent flow should be expressed as an unknown constant. Taking this into consideration, the arithmetically-plotted results of a step-drawdown test can be used to select the discharge rate for a pumping test, determine drawdown for a given pumping rate and optimum pump depth, and even (with some minor calculations) estimate the transmissivity of the formation prior to the test. (This is also a good test for reliability of the flow meter.)

a) Select the pumping rates for the step-drawdown test based on:

   1) production capability estimates made during well development,

   2) prior pumping information,

   3) slug test data (for small wells), or

   4) a brief, preliminary rate test.

Step tests are most commonly run with three steps at 33, 67 and 100 percent or four steps at 25, 50, 75, and 100 percent of the anticipated maximum rate. Sometimes a step is added at 133 percent for a three-step test or 125 percent for a four-step test and the first step is dropped.

b) Conduct the step test, pumping at each level for 30 to 60 minutes. It is important to run the initial step long enough to establish that the effects of well storage have dissipated, with the remaining steps run for the same duration as the initial step. Although standard practice is to allow a recovery period after each step, practical experience shows that these individual recoveries are not necessary.

c) At the end of the step test, mark the setting of the discharge control valve corresponding to the flow rate for the full-scale pumping test. Secure the valve in that position with wire or tape to prevent inadvertent changes.

d) Allow sufficient time after completion for drawdown to return to static level. Although the time may vary, allow at least one day of recovery after the step-drawdown test has been completed before starting the constant-rate test.

11. Synchronize Watches

Just before the constant-rate test, watches and other time-measurement devices (i.e., dataloggers) should be synchronized so that the time of each reading, electronic and manual, can be referenced to the exact minute and hour that pumping started.

III. CONDUCTING THE TEST

1. Record Information

a) Use appropriate data forms

b) Record all required background information on logs before beginning the test

c) Record time as military (24-hour) time.

d) Ensure that everyone taking manual water-level measurements understands the units of measurement on the device or devices they will use.

2. Keep Pertinent Well Construction Details at Hand

To evaluate data plotted during the test, it may be necessary to have access to well construction information, such as the following:

- Lithologic logs;
- Well depths;
- Screen lengths
- Screen type (slotted, wrapped, opening size)
- Filter pack thickness and length
- Pumped well diameter
- Pump characteristics (performance, unit dimensions)
- Pump setting depth
- Topographic maps

3. Start the Test

a) Check all wells to confirm that water is at static level. Record the time since last pumping.

b) Make sure all field personnel are aware of predetermined starting time.

c) Start the pump and timing devices simultaneously. Use both an audible and visible signal to indicate the start of the test, especially if the distance between the pumped well and observation wells is large.

4. Measure Drawdown at Established Times

The widespread use of data loggers with extended memory precludes the older standard of using logarithmic time measurements. However, remember that rapid-frequency readings are needed early in the test in order to observe early effects of pumping and formation storage, plus effects of well construction. Water level measurements should be taken at least every five seconds.

Early time data are of greater importance when conducting pumping tests to identify aquifer heterogeneities and should be collected at short time intervals (< 1 sec) and considered as part of the pumping test analysis. Large data files can be generated and may need to be manipulated with text editors prior to importing data to other software such as Excel.

For manual observation well readings, the following schedule is suggested:

Elapsed Time	Interval Between (minutes) Measurements (minutes)
0-5	1
5-15	2
15-60	5
60-120	10
120-300	30
300-1440	60
1440-end of test	240

Drawdown readings are sometimes difficult to record at the exact time required by the above schedules. If the designated time for a drawdown reading is missed, take a reading anyway and record the actual time. However, try to follow the established schedule as closely as possible to ease data plotting. Use the following table as a guideline for time measurement accuracy.

5. Check the Flow Measuring Device

Unrecorded fluctuations of pumped well discharge rate can make the test data difficult to interpret. Measure and record discharge every 5 minutes during the beginning of the test. When discharge becomes stable, reduce the frequency to hourly checks.

As water levels decline, the discharge rate may decrease, thus requiring adjustment. Whenever adjusting the flow rate, record water levels in the pumped well before and after each adjustment.

6. Monitor Fuel Levels

When using liquid-fuel-driven engines or generators, monitor and refill fuel tanks as needed to prevent premature termination of the test.

7. Plot Data to Evaluate Trends and Catch Aberrations

a) Begin to tabulate and graph the elapsed time, discharge rate, and pumped well drawdown as early as possible in the test, usually after the first hour of testing.

b) Prepare a plot of the log of drawdown (log10s) versus the log of the ratio of time since pumping started to the square of the distance from the pumped well to the observation well (log10t/r2) on arithmetic graph paper and maintain during the test. Compare this data to basic type curves to detect deviations that may be due to discharge variations or other changes in field conditions that need to be documented. A portable computer and printer ease this plotting for tests with many wells.

c) Keep the plots current throughout the test. This information supports informed, intelligent decisions about test progress and may signal anomalies such as equipment malfunctions or unacceptable flow rate variations. Analysis of these plots may suggest that more data is needed to substantiate conclusions about the groundwater system.

8. Collect Groundwater Samples and Measure Field Parameters

Samples of discharge water may provide valuable information about the nature of aquifer water quality as it changes during the pumping test. Depending on the site conditions, samples collected regularly throughout the test may signal proximity to a contaminant source, connection with surface water bodies, or other contributors to water quality change. The number of water samples needed and the frequency and time of their collection depends on both nearness to suspected or known water quality influences and the test budget.

9. Verify Measuring Device Accuracy

Recheck the accuracy of hand-held electronic water-level sounders before starting the recovery portion of the test. During pumping and recovery, check transducer accuracy periodically with reliable manual devices. Every hour or few hours is sufficient for most tests.

10. Measure Water Levels during the Recovery Phase at Established Times

Recovery of water levels following the pumping phase should be measured immediately upon pump shut down and recorded for a period of time equal to the pumping time, or until the water levels have reached 95 percent of the initial, pre-pumping static water level. Use the same drawdown measurement schedule that was used during pumping. A check valve should be used to prevent backflow of water in the riser pipe into the well, which could result in unreliable recovery data.

Recovery phase data may be easier to analyze because no discharge fluctuations occur, and pump-induced turbulence is not a concern in the pumping well. However, note that typically the calculated transmissivity from the pumping phase will be lower than that of the recovery phase due to the added turbulence and vertical flow components during pumping.

11. Record Observation of Pertinent Phenomena

Record any unusual events occurring just before or during the test that may affect test data, such as:

- Weather changes
- Heavy equipment (trains, etc.) passing through area
- Operation times of other wells
- Changes in pumping rate
- Equipment problems, and
- Earthquakes

IV. POST-TEST PROCEDURES

1. Document the “As-Built” Configuration of the Test

Describe the configuration of the test, the observation well locations versus the pumping well, water discharge, outside influences detected during the test, and any modifications to the original plan.

2. Verify Timing Device Agreement and Measuring Device Accuracy

Compare all clocks, watches, and data recorders for agreement and note any discrepancies, identifying the devices and where they were used. Compare manual measurements to datalogger measurements within wells to confirm accuracy of measuring devices.

3. Sound the Pumped Well

Determine if any aquifer material accumulated in the pumped well during the test. Sand or other material accumulating in the well during the test progressively blocks screen areas, reducing the effective aquifer penetration. If the effect of this condition is not taken into account, aquifer parameters calculated from test data will be wrong. Gradually decreasing aquifer penetration in a pumped well significantly complicates test data analysis. The wisest strategy, therefore, is to prevent infilling of screens by sufficient development of the pumped well.

4. Decontaminate All Equipment Contacting Site Groundwater and Soil

Use appropriate decontamination procedures.

5. Monitor Background Information as Long as Possible

If possible, continue to monitor groundwater levels, surface water levels, and barometric pressure data for several days after test completion. This information may reveal trends or relationships undetected before or during the test.

V. SPECIAL CONSIDERATIONS

1. Wells Containing Floating Nonaqueous Phase Liquids

It is best to use pressure transducers to measure water levels in wells containing floating product such as gasoline. Contact with floating product, however, may make transducers and cable unsuitable for future use. Thus, include the cost of replacing transducers (and perhaps cable) when calculating pumping test budgets. Otherwise, protect each transducer and cable assembly by encasing it in plastic tubing or pipe. Be sure that each protected transducer still can respond accurately to any pressure changes.

As an alternative to pressure transducers, make manual measurements (using a interface probe) of both the fuel level and water level individually. Then correct the observed thickness of floating product by its density to arrive at an effective pumping level. Measure product density in the field using a simple density balance (such as drilling fluid balance) or consult an appropriate API table. This manual procedure will work, but takes time and introduces additional measurement and computation errors.

2. Fill Materials

Occasionally, pumping tests are conducted in or adjacent to fill materials. In these circumstances, it is essential that the nature of the fill and possible extremes in heterogeneity be understood and incorporated into the design of the pumping test so that the resulting data set can provide the required information.

3. Karst and Cavernous Aquifers

Flow through the fractures and conduits within a karst aquifer system ranges from conduit to diffuse. Conduit flow describes flow through dissolution channels with velocities commonly high and turbulent. (The presence of conduits typically requires a dual-porosity model for characterization). Diffuse flow, on the other hand, refers to a slow, mostly laminar to slightly turbulent flow through a series of small, discrete pathways that are being enlarged through dissolution. Karst aquifers do not lend themselves to conventional pumping test layout, procedures, and analysis because flow can be dominated by discrete channels. The discrete nature of high-conductivity zones can range several orders of magnitude and thus hydraulic conductivity values vary according to the scale of measurement, from local to regional. Interpretation of pumping tests must take into consideration the portion of the aquifer being tested.

Additional background investigations may need to be conducted before a pumping test is conducted, in order to predict the connectivity of the wells within the test network. This may include borehole and surface geophysics, tracer (natural and introduced) testing, spring flow and water chemistry analysis, slug testing, and lineament analysis.

4. Fractured Aquifers

The challenge to conducting a pumping test within a fractured-rock aquifer is the continuity of fractures can vary significantly within an area and affect its ability to provide water in a consistent manner. Many fractured aquifers also exhibit a preferred permeability direction based on predominant fracture orientations. Recharge may also vary seasonally and cause production problems in low flow periods (low water level and low recharge). During these periods excessive drawdown may occur. Typically, sources completed in bedrock composed of shale, basalt, granite or any consolidated material can have fractured flow concerns.

For these aquifer systems, although a conventional pumping test approach is generally appropriate, more observation wells will be required to determine the anisotropy and to discern both near-well and distant responses. Also, step-drawdown test data provide valuable information in fractured aquifers because flow near the well in fractured aquifers may be mostly turbulent.

VI. REFERENCES

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