Hydrogeologic Investigation of the Sand Lake Area, Anchorage, Alaska

For

Sand Lake Community Council

Municipality of Anchorage

and

State of Alaska

Prepared by:

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INTRODUCTION

This report presents the results of an investigation of groundwater resources in the Sand Lake area of Anchorage between 2012 and 2021 (see Figure 1). The investigation was prompted by concerns of local residents regarding potential water-quality impacts from local development, including large-scale residential development in the former Sand Lake gravel pits, rerouting of urban stormwater runoff into a pond thought to provide recharge to the local aquifer, and construction of an "inert" materials landfill near areas served by private wells. In addition, prior studies have shown that numerous wells serving individual residences in the area have naturally-occurring but elevated levels of arsenic above maximum contaminant levels that are applicable to public water supplies. There is no maximum contaminant level for arsenic applicable to wells serving single family dwellings in Anchorage.

Previous studies have shown that the Sand Lake area is underlain by a complex of glacially-related deposits that have not previously been mapped in detail because of their complexity and a paucity of data in key areas. Groundwater flow directions in site-specific studies have also been shown to be very complex. These uncertainties have made it very difficult to reliably assess risks of well water contamination from potential contaminant sources.

This report consists of this pdf-format file with text and selected inserted figures. Other figures, appendices, and appendix attachments are contained in separate pdf-format files.

Acknowledgements

Funding for this investigation was provided by a grant from the State of Alaska through the Municipality of Anchorage and the Federation of Community Councils and with the guidance and support of the Sand Lake Community Council. Work was performed and supported by numerous student research assistants at the University of Alaska Anchorage Department of Geological Sciences under the guidance of Professor Dr. LeeAnn Munk, who contributed greatly to this project by overseeing the well sampling and analysis program and other tasks. Additional UAA students and staff contributing to this project included undergraduate students Dale Patrick, Rebecca Reyes, Justin Mark, Jordan Jenkes, and Sydney Souza; graduate students Dustin Murray and Patrick Foster; Research Associate Molly Reeves; and Associate Professor Dr. Matt Reeves. Cooperation of numerous homeowners for access to their wells for sampling and water-level measurements is greatly appreciated. The Municipality of Anchorage also supported the project by providing access to municipal lands for test-well installation, pumping, sampling, and monitoring. Assistance in preparing maps for this report was provided by Alaska Map Science of Anchorage and is greatly appreciated.

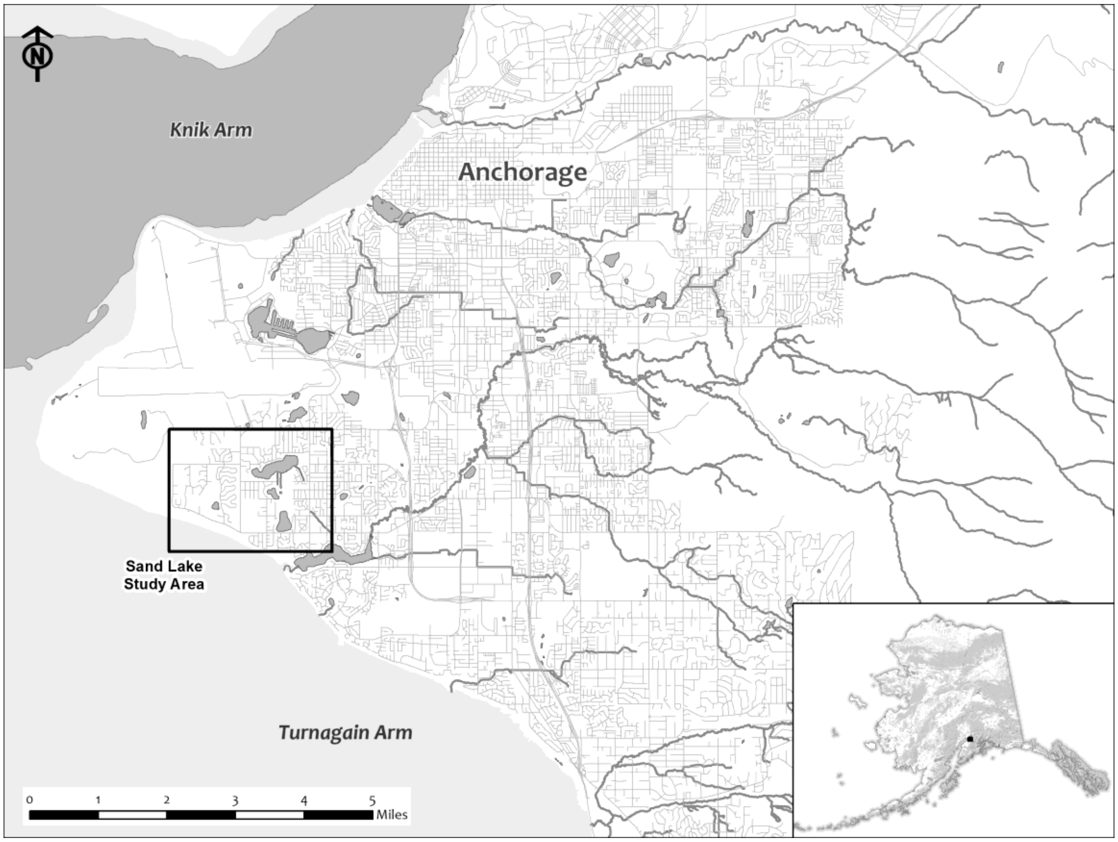


Figure 1. Location of the Sand Lake study area.

Study goals, objectives, and scope of work

The primary objectives of the study were to:

- install a system of geological test holes and monitoring wells that can be used to better understand the complex glacial stratigraphy and occurrence of aquifers and confining units in the Sand Lake area and to monitor changes in water levels and water quality over time;
- determine directions of groundwater flow;
- improve the understanding of likely interconnections of aquifers; and
- obtain baseline groundwater quality information from residential wells in the area.

This information would then be available to perform risk assessments for water wells in the area, although this is beyond the scope of the current study. The information would also be useful for conducting groundwater protection measures.

This study drilled and installed seven monitoring wells in five boreholes (two wells were dual-completion wells), performed a surface geophysical investigation, sampled numerous private wells, monitored long-term water-level fluctuations, performed a large-scale aquifer test, and performed a synoptic water-level survey in order to prepare maps of the water table surface for the unconfined aquifer and the potentiometric surface of confined aquifers, and to infer directions of groundwater flow.

The findings of the investigation were also used to evaluate reports of contamination of wells by sediment from gravel mining operations. The evaluation included a literature review of particulate transport in aquifers, compilation of resident's observations, and a review of prior evaluations of the events.

This project assembled and analyzed the most extensive database of well logs yet assembled to better understand local aquifer and confining unit stratigraphy. Additionally, quarterly sampling was performed from monitoring wells for one year, including some wells drilled during prior studies, to determine potential seasonal fluctuations in groundwater quality.

METHODS

Well log database development

Logs of wells drilled in the study area were assembled from prior reports and agency databases. More than 300 wells in the study area with well logs were identified, located, and plotted on maps (Figures 2, 2a, 2b, 2c, 2d, 2e, 2f, and 2g). Many of the wells were field-visited; the locations of others were determined from as-built property diagrams found in Municipal on-site records. In general, well locations were not surveyed and locations shown on Figure 2 and inset maps are approximate.

Many of the records were not contained in any prior study dataset. Prior studies have used at least six different well identification schemes to relate locations on maps to well logs in a dataset. This has created considerable confusion in tracking individual records of wells. This study uses the State of Alaska WELTS system operated by the Alaska Hydrologic Survey, which is the most widely-available and widely-used well record locator system in Alaska. Each well log can be accessed on line (https://dnr.alaska.gov/welts/#show-welts-intro-template) by means of a unique Log ID shown in Appendix A that has been assigned by the WELTS system (WELTS is short for "Well Log Tracking System"). A few wells in the dataset have no well logs, and thus no WELTS entry.

For ease of matching well data shown on maps, however, with records in Appendix A, a system based loosely on Subdivision-Lot-Block is used for most wells. Usually, a one- to three-letter abbreviation of the subdivision name is followed by the block number or letter (if there is one), a dash, and the lot number. Some wells, particularly older wells found in the USGS system, are described by an abbreviated version of the Local Number used by the USGS to uniquely identify each well using the township-range-section and fourth-order aliquot part of a section system. Project-specific monitoring wells are generally assigned the names of the wells that were assigned by the consultants performing the studies.

One of the challenges of prior investigations was inaccuracies in determining land surface elevations for the wells. During this study, elevations of land surface at well sites were determined using a 2-ft contour-interval lidar topographic map obtained from the Municipality of Anchorage. The map uses the NAD83 horizontal datum and the Municipality's 1972 vertical datum (MOA 72 Adjustment, or MOA72 for this report). The topographic map used for this project is very similar to a more recent lidar topographic map produced in 2015 and found on the Municipality of Anchorage website: https://muniorg.maps.arcgis.com/apps/Profile/index.html?appid=d513adf90dd04c29be5e5d78a1587200.

Some data obtained from the USGS uses the NGVD 1929 vertical datum, which is similar to the MOA 72 Adjustment. The other datum in common use is the NAVD 88 datum, which in the Sand Lake area, is about 6.5 ft higher than the NGVD 1929 datum. The NAVD 88 datum was not used for this project. Latitude and longitude coordinates of some wells were also located using GPS systems.

A complete listing of wells used for the study is provided in Appendix A. Most logs for individual wells are generally available through the Municipality of Anchorage's On Site program, the State of Alaska, Department of Natural Resources (WELTS), or the U. S. Geological Survey National Water Information System databases. All logs in Appendix A have been submitted to the WELTS system and assignment of WELTS numbers.

Data contained in the well records were compiled into a spreadsheet-format database (Appendix A), along with information obtained from water-level surveys. Water quality sampling results are contained in Appendix B. Data reported by Kane and others (2008) is also contained in the database in Appendix B. Well logs were examined to determine the reported top and thickness of interpreted aquifer zones encountered by the wells and the interpreted bottom of the Bootlegger Cove Formation. This information was added to the database in Appendix A.

Test well installation and development

Test wells SL-3, SL-4I, and SL-4D were drilled near the south end of Lucy Street (Figure 2e); test wells SL-5S and SL-5D were drilled near the north end of Sommers Place (Figure 2d); and test wells SL-6S and SL-6D were drilled between Westpark Drive and South Pond (Figure 2). Logs of materials encountered during drilling and well construction information is contained in Appendix C. For completeness, Appendix C also includes test drilling logs of SL-1 and SL-2 (see Figure 2d) performed as part of an earlier study (Munk and others, 2010). Interpreted formation contacts for the test wells are provided in Appendix A.

All test wells drilled for this project were installed by air-rotary drilling and were cased with 6-inch inside-diameter steel casing. They were grouted with bentonite grout using the dry-driven grout method. Wells SL-1, SL-3, and SL-6S were completed with open ends and developed with natural gravel packs. Wells SL-4I, SL-4D, SL-5S and SL-5D were perforated and completed as dual completion monitoring wells using 2-inch diameter PVC inner casing and screen that was sealed from other water-bearing zones with bentonite. Wells SL-2 and SL-6D were completed with well screens so that larger amounts of water could be pumped. Well drilling observation and geologic sample logging was performed on-site during drilling by a student or professional research associate from the University of Alaska Anchorage Department of Geological Sciences and periodically inspected and overseen by an Alaska-licensed professional geologist. Wells were developed with air-lift methods and purged with a purge pump prior to sampling.

Water sampling

Private domestic wells were sampled during at locations shown in Figure 3. Results of laboratory analyses of water samples are shown in Appendix B. All water samples were analyzed at the University of Alaska Anchorage Applied Science and Technology (ASET) laboratory with the exception of the tritium samples, which were analyzed at the Noble Gas Laboratory at the University of Utah.

Field and Laboratory Methods. In situ measurements of static groundwater level were made with an electric water-level indicator or a sonic sounder prior to purging the well and sampling the groundwater. Other field measurements taken during each sampling event included pH, dissolved oxygen, specific conductance, and temperature. Alkalinity was also measured at the time of sampling using a portable titrating kit, following standard methods outlined in Munk and others (2011) and modified USGS methods from Koterba and others (1995).

Water samples were collected in cleaned high density polyethylene (HDPE) bottles for dissolved elemental concentrations and anions. The sample bottles were rinsed on site with the sample water three times prior to collection of the sample. The water samples for dissolved element analysis were filtered using a 0.45 µm membrane and were preserved using ultrapure nitric acid, and brought to pH less than 2.0. Another filtered but unacidified sample was collected for anion analysis. All samples were stored at 4°C from the time of collection until time of analysis at the UAA ASET Laboratory. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was used for elemental concentration determination and Ion Chromatography (IC) for anion concentrations.

The tritium samples were collected in one liter sample bottles and shipped to the Noble Gas Laboratory at the University of Utah where they were analyzed for tritium content.

Duplicate samples were analyzed for major and trace element and indicate that the percent differences between the duplicate and the primary samples are less than or equal to 5%, indicating very high quality of the data. Additionally, all calibration check verification standards and blanks that were run with the samples for multi-element analysis by ICP-MS indicate acceptable recoveries and below detection results, respectively.

Water-level measurements and monitoring

Pressure transducers were installed in the wells drilled for this study, and also in Wells SL-1, SL-2, KE-21 and KE-22 (Figure 2d). The results of the water level monitoring are presented in Appendix E. A near-synoptic water-level survey was conducted during May and June 2015, measuring water levels in wells over a relatively brief period of time so that seasonal or multi-year fluctuations would not affect determinations of the water table or potentiometric surfaces of aquifers.

Geophysical Studies

A geophysical study using an electrical resistivity method was performed along 4 transects through the study area to obtain a better understanding of local stratigraphy and water saturation.

PREVIOUS WORK AND CONCEPTUAL HYDROGEOLOGIC MODEL

Extensive summaries of the geology and hydrogeology of Anchorage and southwest Anchorage have been presented including Miller and Dobrovolny (1959), Trainer and Waller (1965), Barnwell and others (1972), Ulery and Updike (1983), Schmoll and Barnwell (1984), Updike and Ulery (1986), Schmoll and others (1999), Munk and others (2004), Moran and Galloway (2006), Patrick and others (1989), Kane and others (2008), and Munk and others (2010) and are briefly recapped here in order to establish a general hydrogeologic framework and conceptual model for the area.

Unconsolidated deposits are reported to be up to approximately 1050 feet thick in the study area based on an exploratory oil well drilled in the former Sand Lake gravel pit in the 1960s (Well_ID Pan Am, Appendix A). Sedimentary rocks of the Kenai Group underlie the glacial sediments. The deepest water well record identified during this investigation is from a well drilled for Dimond High School (just east of the study area) in 1967 that was drilled to a depth of 597 feet.

No water wells in the study area are reported to penetrate lithified rock formations.

The Anchorage confined aquifer system (Patrick and others, 1989) is a confined sand and gravel aquifer consisting of multiple layers of water-producing sand and gravel interbedded with diamicton and other silty units. Wells tapping the confined system have historically provided water to numerous public and private water supply-systems in Anchorage and have been extensively investigated, mostly in areas of Anchorage east and northeast of the Sand Lake study area (Barnwell and others, 1972, Patrick and others, 1989).

These sands and gravel units are considered to be the result of glacial outwash or alluvial sources derived from glaciers that have mountain sources surrounding upper Cook Inlet and Anchorage (Schmoll and others, 1999). Schmoll and Barnwell (1984) estimated that the layered sediments likely represent five to seven separate episodes of glacial advance and retreat during the Pleistocene Epoch. This conceptual model of numerous separate advance/retreat cycles, while identified in North Anchorage, is considered to be potentially applicable to the deposits in the Sand Lake area that are in the same depositional basin.

During the period of Pleistocene glaciation in Anchorage, several processes may have complexly interacted to make the position of sea level relative to land surface different than it is today (Schmoll and others, 1999). These include: 1) the lowering of eustatic sea level caused by global ice ages that tie up some of the planet's water in ice; 2) isostatic change in land surface caused by local depression of the earth's crust by ice masses on land during ice ages and rebound of the land surface for thousands of years after glaciers melt; and 3) tectonic land surface change caused by regional uplift or sinking of the land surface. For example, Anchorage experienced 3.7 feet of tectonic subsidence from the March 27,1964, Alaska earthquake (Waller, 1966). Also, Schmoll and others (1999) postulated the possible presence of a basin in Anchorage caused by uplift at Fire Island and normal faulting (mountains raised up and lowlands lowered, relatively) along the Chugach Mountain front in east Anchorage. Such relative sinking of the land surface during the Pleistocene could explain the thick sequence of glacial deposits found in the study area that extend almost 1000 feet below modern sea level.

Numerous geologists have attempted to correlate subsurface deposits identified in well logs with surface expressions of glacial moraines in Alaska and glacial episodes during the Pleistocene elsewhere in North America. These correlations are very difficult and generally not very successful because subsurface deposits can usually not be traced to surface moraines in the Anchorage area and many of the surface moraines seem to be younger than the subsurface deposits (Schmoll and others, 1999). Age dating of subsurface deposits is difficult and has not been accomplished.

Bootlegger Cove Formation (BCF)

The BCF is mapped as the surficial geologic unit across most of the study area (Updike and Ulery, 1986; Figures 4a, 4b, and 4c) and is of critical importance in understanding groundwater in the area. The BCF has long been recognized as a key geologic unit throughout much of Anchorage as a confining unit that directly overlies the Anchorage confined aquifer system and also because of its role in causing ground failures and landslides in Anchorage during the 1964 earthquake. Trainer and Waller (1965) provided a description of the unit (which they called the Bootlegger Cove Clay) and produced structure contour maps of both the top and the base of the unit throughout its area of occurrence in the Anchorage lowland, including the Sand Lake area. While data were sparse in the Sand Lake area compared to what has become available since the 1960s, Trainer and Waller (1965) showed the thickness of the unit to be between 100 and 200 feet in the Sand Lake area, which is generally consistent with the findings of subsequent investigators and this report. Most water wells in the Sand Lake area were drilled through the BCF and into the underlying Anchorage confined aquifer system, although some wells obtain water from sandy and gravelly units within the BCF.

Figure 4a. Geologic map of the Sand Lake study area. See Figure 4c for a description of the map units (modified from Updike and Ulery, 1986).

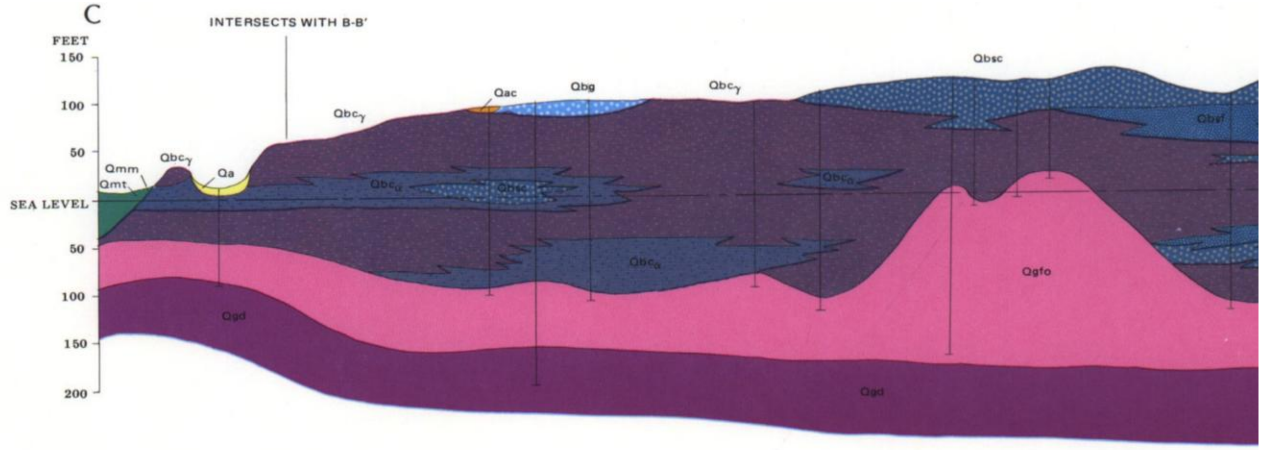
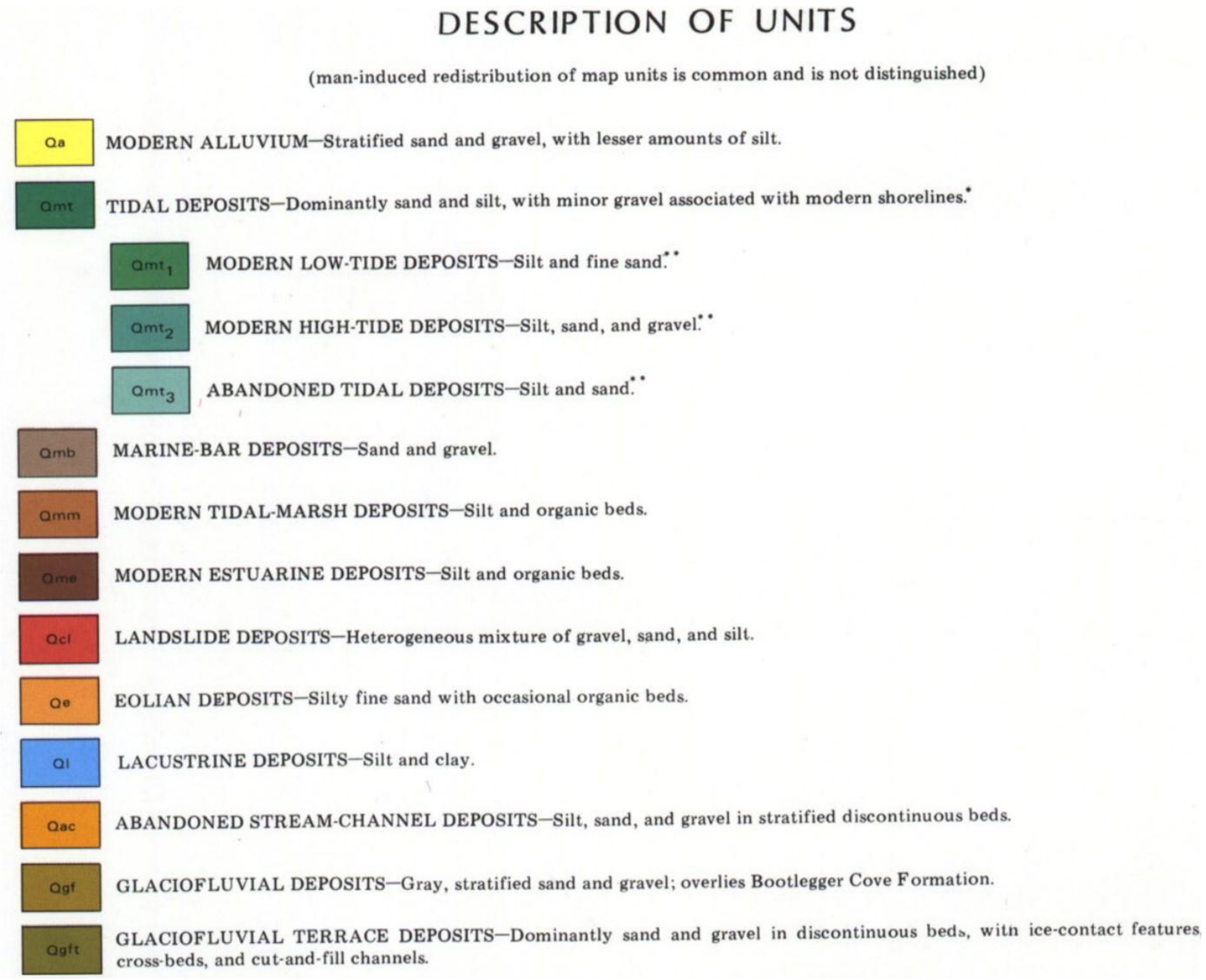


Figure 4b. Portion of geologic cross section C-C'. See line of cross section oriented approximately N13ºE located east of Jewel Lake and Sand Lake on Figure 4a. See Figure 4c for description of the cross section units (modified from Updike and Ulery, 1986).

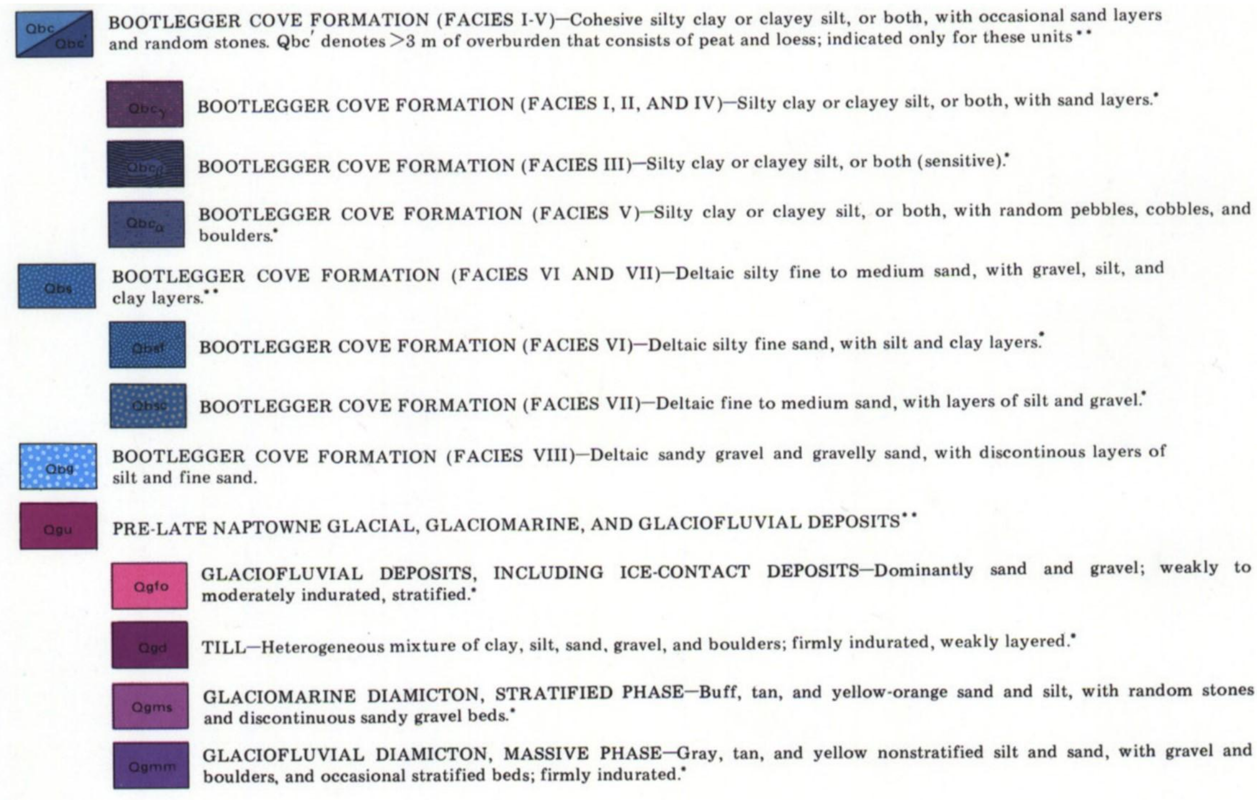


DESCRIPTION OF UNITS

(man-induced redistribution of map units is common and is not distinguished)

Qa	**MODERN ALLUVIUM**—Stratified sand and gravel, with lesser amounts of silt.
Qmt	**TIDAL DEPOSITS**—Dominantly sand and silt, with minor gravel associated with modern shorelines.*
Qmt_1	**MODERN LOW-TIDE DEPOSITS**—Silt and fine sand.**
Qmt_2	**MODERN HIGH-TIDE DEPOSITS**—Silt, sand, and gravel.**
Qmt_3	**ABANDONED TIDAL DEPOSITS**—Silt and sand.**
Qmb	**MARINE-BAR DEPOSITS**—Sand and gravel.
Qmm	**MODERN TIDAL-MARSH DEPOSITS**—Silt and organic beds.
Qme	**MODERN ESTUARINE DEPOSITS**—Silt and organic beds.
Qcl	**LANDSLIDE DEPOSITS**—Heterogeneous mixture of gravel, sand, and silt.
Qe	**EOLIAN DEPOSITS**—Silty fine sand with occasional organic beds.
Ql	**LACUSTRINE DEPOSITS**—Silt and clay.
Qac	**ABANDONED STREAM-CHANNEL DEPOSITS**—Silt, sand, and gravel in stratified discontinuous beds.
Qgf	**GLACIOFLUVIAL DEPOSITS**—Gray, stratified sand and gravel; overlies Bootlegger Cove Formation.
Qgft	**GLACIOFLUVIAL TERRACE DEPOSITS**—Dominantly sand and gravel in discontinuous beds, with ice-contact features, cross-beds, and cut-and-fill channels.

Figure 4c. Description of units for Figures 4a and 4b (modified from Updike and Ulery, 1986).



Qbc Qbc'	BOOTLEGGER COVE FORMATION (FACIES I-V)—Cohesive silty clay or clayey silt, or both, with occasional sand layers and random stones. Qbc′ denotes >3 m of overburden that consists of peat and loess; indicated only for these units**
Qbc_{γ}	BOOTLEGGER COVE FORMATION (FACIES I, II, AND IV)—Silty clay or clayey silt, or both, with sand layers.*
Qbc_{β}	BOOTLEGGER COVE FORMATION (FACIES III)—Silty clay or clayey silt, or both (sensitive).*
Qbc_{α}	BOOTLEGGER COVE FORMATION (FACIES V)—Silty clay or clayey silt, or both, with random pebbles, cobbles, and boulders.*
Qbs	BOOTLEGGER COVE FORMATION (FACIES VI AND VII)—Deltaic silty fine to medium sand, with gravel, silt, and clay layers.**
Qbsf	BOOTLEGGER COVE FORMATION (FACIES VI)—Deltaic silty fine sand, with silt and clay layers.*
Qbsc	BOOTLEGGER COVE FORMATION (FACIES VII)—Deltaic fine to medium sand, with layers of silt and gravel.*
Qbg	BOOTLEGGER COVE FORMATION (FACIES VIII)—Deltaic sandy gravel and gravelly sand, with discontinous layers of silt and fine sand.
Qgu	PRE-LATE NAPTOWNE GLACIAL, GLACIOMARINE, AND GLACIOFLUVIAL DEPOSITS**
Qgfo	GLACIOFLUVIAL DEPOSITS, INCLUDING ICE-CONTACT DEPOSITS—Dominantly sand and gravel; weakly to moderately indurated, stratified.*
Qgd	TILL—Heterogeneous mixture of clay, silt, sand, gravel, and boulders; firmly indurated, weakly layered.*
Qgms	GLACIOMARINE DIAMICTON, STRATIFIED PHASE—Buff, tan, and yellow-orange sand and silt, with random stones and discontinuous sandy gravel beds.*
Qgmm	GLACIOFLUVIAL DIAMICTON, MASSIVE PHASE—Gray, tan, and yellow nonstratified silt and sand, with gravel and boulders, and occasional stratified beds; firmly indurated.*

Figure 4c (continued). Description of units for Figures 4a and 4b (modified from Updike and Ulery, 1986).

The BCF is of late Pleistocene age and appears to have been deposited between approximately 20,000-14,000 years before present (Schmoll and others, 1999). Part of this formation, across most of the Anchorage lowland, was deposited in mostly marine but possibly also lacustrine conditions and is characterized where it outcrops in north Anchorage by five fine-grained facies (Facies I-V) predominantly comprised of silt and clay, but also containing minor sand and pebbles in varying amounts and arrangements. A sedimentary facies is a distinctive rock (or sediment) unit that forms under certain conditions of sedimentation, reflecting a particular process or environment (https://en.wikipedia.org/wiki/Facies).

Failure of sensitive clays or liquefaction in the BCF are considered to have caused the three major landslides in north Anchorage during the 1964 earthquake (Updike and Ulery, 1986); the Turnagain landslide, the L Street landslide, and the 4th Avenue landslide. Subsequent studies of the BCF have extended to southwest Anchorage including the Sand Lake area, where three additional facies have been recognized. In southwest Anchorage, the BCF confining layers undergo a lateral facies change from east to west (Ulery and Updike, 1983; Figure 5). The sediments change from the predominantly silt and clay facies in the east through a transition zone to more permeable sediments (silty sands, sands, and gravels) in Facies VI-VIII in the west. These facies are interpreted to have been deposited as a glacial fan-delta into a marine or glacial-lake environment from a glacial source located to the west of the study area. The coarsergrained facies are common in the western part of the study area of this project and are important for understanding groundwater occurrence and flow systems there.

After the fan-delta deposits of the BCF were deposited, some of them were reworked by running water and transported to overlie the slightly older fan-delta deposits. These deposits, largely sand and gravel, occur in the former Sand Lake gravel pits and are the source of sand and gravel mined there. They are included by Updike and Ulery (1986) as part of the BCF. Thus, the stratigraphy at the former Sand Lake pits can include permeable sands and gravels overlying fan-delta and deeper-water silty sediments, both within the BCF, which unconformably overlie older (pre-BCF) sands and gravels of the Anchorage confined aquifer system. Updike and Ulery (1986) noted that there is relief on the unconformity surface below the BCF, which this study has generally confirmed with some differences noted in some areas.

Two-aquifer conceptual model and the water-table aquifer

Based on stratigraphic relationships described above and similar relationships elsewhere in Anchorage, Barnwell and others (1972) and Patrick and others (1989) present a two-aquifer conceptual model. Near-surface sands and gravels host a water-table aquifer that overlies the BCF silt and clay confining unit. The water table is defined as the upper surface of a zone where sediments are fully saturated with water. The near-surface sand and gravel water-table aquifer is not present everywhere, but is commonly associated with modern stream courses, abandoned channels such as in the old Sand Lake gravel pits, or broad outwash deposits in front of features such as the Elmendorf Moraine. In some places, fine-grained glacial till or silty deposits of the BCF are present near the land surface and the exact position of the water table is difficult to determine. Beneath the confining units of the BCF is a sequence of sand and gravel zones separated by confining layers that constitute the Anchorage confined aquifer system. This two-aquifer conceptual model was found during this study to generally apply to the Sand Lake study area.

Anchorage confined aquifer system

Below the BCF, an areally-extensive deposit of glacial outwash or glaciofluvial sand and gravel interbedded with other sediments constitutes the Anchorage confined aquifer system. Barnwell and others (1972) recognized that the confined aquifer transitions to a "partly confined" aquifer west of Sand Lake as the fine-grained deposits of the Bootlegger confining unit "thin out" or "grade to more permeable sediments" to the west. Zenone (1976) slightly modifies this description by identifying "the approximate western extent" of the two-aquifer system (confined and unconfined) along a north-south-oriented boundary near the western shores of Sand Lake, Sundi Lake, and Jewel Lake. The boundary identified by Zenone (1976) approximately coincides with the eastern edge of the area Ulery and Updike (1983) mapped as a "transition zone" (Figure 5).

Munk and others (2004) constructed several cross sections to investigate the characteristics of confining layers across the transition zone in the area of the then-proposed Kincaid Estates subdivision and their possible role in protecting deeper aquifers from contamination related to development. They noted that Ulery and Updike (1983) described the transition zone as a zone between areas where the cohesive facies predominates (in the east) and areas where the non-cohesive facies predominate (in the west), a characterization with which they concurred.

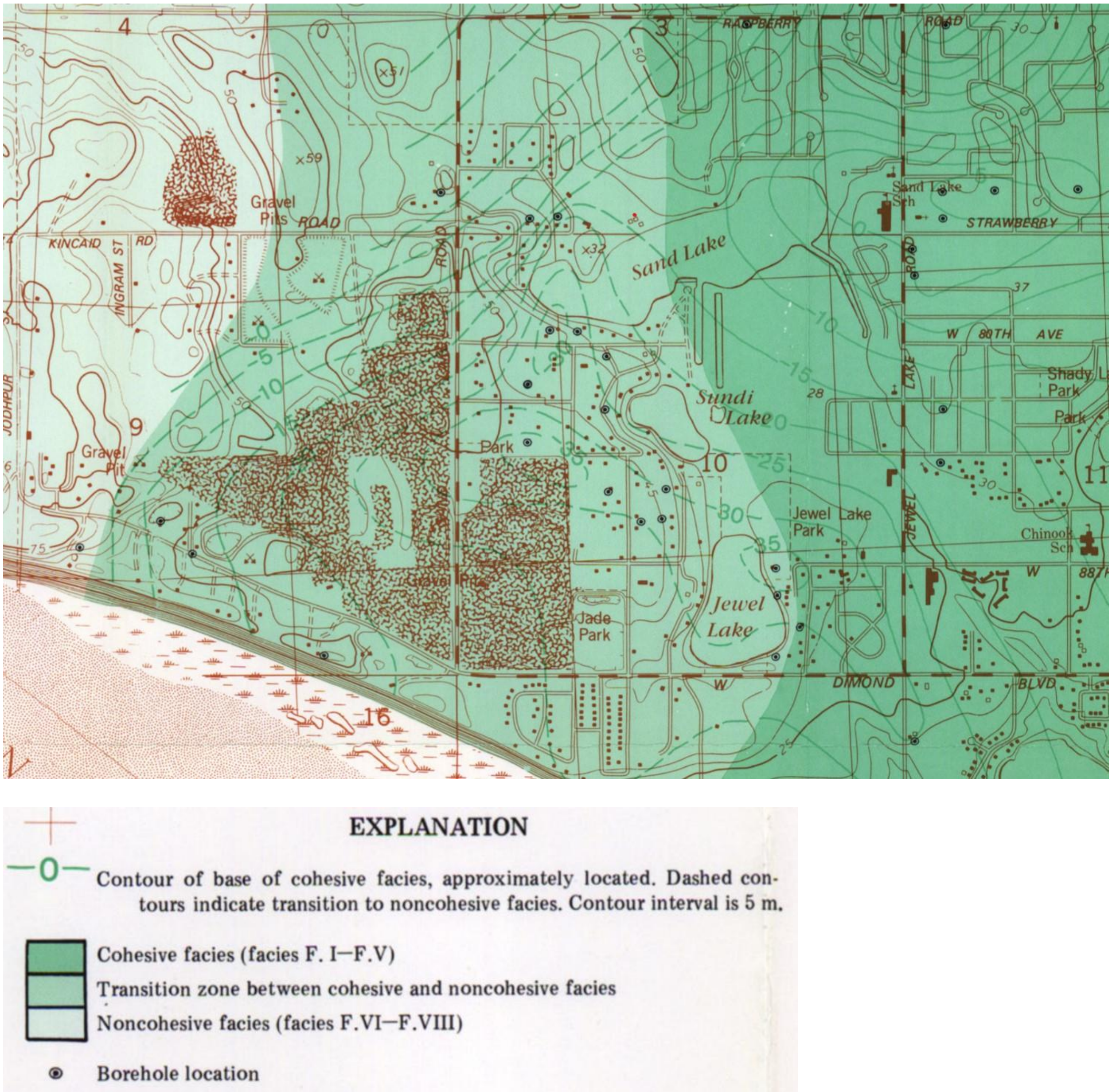


Figure 5. Subsurface structure contour map of the base of the cohesive facies of the Bootlegger Cove Formation (modified from Ulery and Updike, 1983).

Munk and others (2004) concluded that:

> The cohesive facies identified by Ulery and Updike (1983) and used in the conceptual hydrologic model of Barnwell et al. (1972) as the continuous confining layer is discontinuous in the geologic transition zone of Sand Lake area and is unknown across the site of the proposed subdivision. Because only three wells (700009, 700027, and 700033) extend into the deeper parts of the aquifer system, there is a lack of data for understanding the deeper hydrostratigraphic units at the site of the proposed subdivision. Therefore it is impossible to confidently determine continuity of the low and high permeability units across the site area with the existing data.

Kane and others (2008) also review numerous well logs in their study area (which approximately matches the study area of this project) and concluded that aquifers and confining units appeared to be discontinuous across the study area, but that it was possible to draw a potentiometric surface map to generally identify groundwater flow directions. Localized groundwater flow directions were difficult to predict because of an incomplete understanding of the complex hydrostratigraphy.

One complication to the two-aquifer conceptual model in the Sand Lake study area is that the lower portions of the Bootlegger Cove Formation, in some areas, appear to be comprised of permeable sand and gravel deposits that directly overlie the permeable sand and gravel deposits of older deposits. Also, the older sands and gravels (map unit Qgfo of Updike and Ulery, 1986) appear to represent an unconformity with substantial local relief. Thus, it is difficult to distinguish between basal coarse facies of the Bootlegger Cove Formation and underlying sands and gravels that correlate with the Anchorage confined aquifer system. In these places, the older aquifer deposits of the Anchorage confined aquifer system and the younger permeable BCF deposits comprise a single hydrostratigraphic unit. To further complicate matters, in some areas there may be no confining or semiconfining unit present and a single hydrostratigraphic unit occurs under water-table conditions.

RESULTS

This study has generally confirmed the geological setting and conceptual model described by prior investigators. The test drilling, aquifer testing, water-level monitoring and analysis of area well logs has added considerable detail, clarity, and a few corrections to prior characterizations and mapping, however.

Well log analysis and mapping of the BCF and the upper zone of the Anchorage confined aquifer system

Analysis of well-log data from private wells reveals that drillers have commonly identified a distinctive change in lithology and texture when encountering sediments that appear to be immediately below the BCF. This has facilitated area-wide interpretation of the base of the

BCF. Above this contact, drillers frequently described sediments as "soft" and consisting of silts and clays, but including "runny" or "heaving" sands. These are the types of sediments that would be expected to be deposited in a lacustrine or marine deltaic environment.

Below the contact, drillers commonly describe materials as hardpan, sand and gravel, or sand and gravel with varying amounts of silt, or till. The sand and gravel can either be water-yielding to constitute an aquifer, or may be too silty to quickly yield sediment-free water without a well screen. In this case, drillers commonly drilled deeper. The deposits beneath the BCF are interpreted to consist of glacioalluvium or diamicton (till). Closely spaced wells commonly describe the contact at the base of the BCF at similar depths. Consistent with previous investigators, the base of the BCF is interpreted to be an unconformity. Figures 6 and 6a are maps showing structure contours of the base of the BCF. Construction of this map, based on many closely spaced well and stratigraphic test drilling at key locations, shows that the cohesive facies of the BCF extends further west than was recognized by Ulery and Updike (1983). Two cross sections (Figures 7 and 8) illustrate the interpreted location of the contact between the BCF and underlying deposits and the configurations of deposits within the BCF. For example, Figures 7 and 8 show the facies changes within the BCF, where sediments transition from predominantly silty sand, sand, and gravel in the west to silt and clay in the east.

Figures 6 and 6a are similar to a map showing subsurface structure contours of the base of the cohesive facies by Ulery and Updike (1983) except for several differences:

- Figures 6 and 6a show the base of the formation throughout the study area;
- Many more well logs were used to construct Figures 6 and 6a than were available for Ulery and Updike's (1983) work. This provides considerable additional detail of the contours that show the configuration of the surface. There are remarkably consistent interpretations of the location of the base of the BCF because of the high density of water-well logs spanning more than 70 years of drilling activity by many different water-well drillers.
- Ulery and Updike (1983) interpreted a relative "high" in the base of the cohesive zone rising to more than 15 feet above sea level along Strawberry Road just east of Sand Lake School (see Cross Section in Figure 4b). Their subsurface data have been supplemented with numerous newer or recently available and closely-spaced well logs. The surface in this area has been reinterpreted to be a relatively flat-lying surface about 100 feet below sea level. The well logs that penetrated sand and gravel deposits that Ulery and Updike (1983) interpreted as being just below the base of the BCF are in this report interpreted as "Intra-bootlegger aquifers". Closely spaced wells unavailable to Ulery and Updike (1983) in this area have shown the presence of a much greater thickness of BCF silts and clays than was previously recognized.

Geophysical investigations

Geophysical investigations are potentially useful for confirming conceptual models and understanding the hydrogeology of the Sand Lake area. A geophysical survey consisting of Electrical Resistivity Tomography was used along four transects in the study area (Appendix D).

Line 4 of the geophysical survey is the most informative transect as a result of the longer length (830 meters) and thus greater depth of investigation. All lines, however, confirm the general hydrogeologic conceptual models described in this report:

1) Surficial deposits in the former Sand Lake gravel pit area consist mostly of reworked sands and gravels with relatively high resistivity (yellows and reds). These deposits occur mostly above sea level.

2) at intermediate depths throughout the area investigated, but especially in the vicinity of the South Pond, deposits of low and intermediate resistivity (blue and green) are found. These are interpreted to be saturated.

Water-table aquifer

The two-aquifer conceptual model described by Barnwell and others (1972) and Patrick and others (1989) applies to some areas at Sand Lake, but does not sufficiently describe the complexity of groundwater conditions in the area. In the former Sand Lake gravel pits for example, TERRASAT, Inc. (2003a; 2003b) document the existence of a water-table aquifer underlain by a silty confining unit and a deeper confined aquifer (at Well_ID AA, for example, and later confirmed by test wells SL-6D and SL-6S). In other areas, silty facies of the BCF occur at or near the land surface and the water table is more of a conceptual surface (where the hydraulic head is equal to atmospheric pressure) than an aquifer where sediments will readily yield water to a well. Nevertheless, an area-wide water-table contour map (Figures 9, 9a) is a useful tool for inferring approximate directions of groundwater flow, recharge and discharge relationships to and from the aquifer, and the depth at which groundwater might first be expected to be encountered during drilling.

An approximation of where a sand and gravel water-table aquifer may exist can be determined from a surficial geologic map where map units consisting of the non-cohesive facies (facies VI-VIII) occur (Updike and Ulery, 1986: Figure 4a). The water table aquifer is also shown in Cross Sections A-A' and B-B' (Figures 7 and 8). Although the water table in most of the study area occurs within the BCF, the interpreted base of the BCF is located above the water table in the northern part of the study area in Rolling Hills Estates subdivision (Figures 6, 9, and 11). The water table in this area is found in underlying sands and gravels that are elsewhere considered to be part of the Anchorage confined aquifer system. Another area where the water table aquifer is inferred to be part of the Anchorage confined aquifer system is beneath the South Pond.

Previous water-table contour maps did not encompass the entire Sand Lake study area. Zenone (1976) presents a water-table contour map of the unconfined (water-table) aquifer east of the Sand Lake/Sundi Lake/Jewel Lake north-south alignment, based on an earlier water-table contour map of Anchorage by Dearborn and Freethey (1974). To the west of the lakes an area-wide water table map has not previously been mapped other than at a regional scale with a 50-foot contour interval (Patrick and others, 1989). Local, project-specific water-table contour maps have been presented by TERRASAT, Inc. (2003a; 2003b), and Brailey Hydrologic Consultants (2013; 2014; 2015a; and 2015b). More recently Aerostar SES, LLC (2019) provided a potentiometric contour map for the former Kulis Air Force Base located immediately north of Raspberry Road, which is the north boundary of this project. Aerostar SES, LLC (2019) reported that this contour map represents the surface of the unconfined aquifer. This means that the map is equivalent to the water-table contour map described in this report; technically, a water table is just a special case of a potentiometric surface.

A nearly synoptic (measurements made at the same time) water-level survey was performed during this project, however there were too few wells measured that tapped the water-table aquifer to make an adequate area-wide water-table map. Thus, the data used to construct the water-table map (Figures 9, 9a) were obtained from a variety of sources in order to provide sufficient geographical coverage and data density to construct the map. Data were derived from well drillers logs where a water-table aquifer was encountered, from studies by consultants or by the U.S. Geological Survey, or data were collected during this investigation. The data used to construct Figures 9 and 9a are provided in Appendix A.

In order to evaluate the quality of data used to construct the map, historic data were examined. Numerous hydrographs are available (see Appendix E) to estimate that water levels usually fluctuate by only a few feet seasonally or over multi-year periods, which is small compared to the large overall water-table difference of about 90 feet across the study area. In local areas with relatively flat gradients, however, Aerostar SES, LLC (2019) has shown that seasonal changes to water levels and groundwater flow directions can occur. Brailey (2013), however, showed that seasonal fluctuations did not reflect any significant change in groundwater flow directions in the Lucy Street area. Also, TERRASAT, Inc. (2003a; 2003b) found very consistent groundwater flow directions for five synoptic water-level surveys at the KE series of wells in the central area of the old Sand Lake gravel pit between April 2002 and April 2003. Thus, the data sources used to construct the map were concluded to be of suitable quality for construction of the map.

Overall, the water-table map suggests that shallow groundwater flows from east to west with a southerly direction towards Campbell Lake and a southwesterly direction towards the bluffs along Turnagain Arm. There is an anomalous but well-documented water-table configuration in the vicinity of the former Lucy Pit near Lucy Street (Brailey, 2013). There, many repeated measurements document a persistent southeasterly direction of groundwater flow during each month of a year and during sequential years. Data from December 2012 (Brailey, 2013) were used in Figures 9 and 9a because water levels that year were mid-way between a high-water year and a low-water year (Brailey, 2015a). Brailey (2013) reported that the variation in water levels measured over a twelve months period was less than approximately 0.7 feet. The significance of this anomalous water table configuration is discussed below in conjunction with the potentiometric surface map constructed during this study (see "Potentiometric surface" section below).

Sand Lake, Sundi Lake, and Jewel Lake are all considered to be perched or separated from the main water table by very low permeability materials of the BCF and were not used as contouring boundaries.

The South Pond constitutes an expression of the water table surface of a sand and gravel aquifer, with groundwater interpreted to flow into the pond on the east side and out of the pond on the west and northwest sides. Characterizations of the South Pond as an "exposed aquifer" (see Appendix H) are apt. There are no surface-water streams entering or leaving the South Pond, except that during high-rainfall events a storm-water overflow structure that was constructed in 2016 diverts stormwater runoff into the pond. This occurred once during August 2016 and once again during August 2017, but is not known to have occurred during the subsequent four years. The exact size of storm required to trigger overflow into the pond is not known.

A relatively high area of the water table (around 100 feet above msl) east of Sand Lake closely matches a similar contour shown by Dearborn and Freethey (1974), which is likely based on data from the same well as shown in Figure 9. This type of closed contour feature is generally considered to be indicative of local groundwater recharge.

Cross sections A-A' and B-B' (Figures 7 and 8) illustrate relationships between the water table aquifer and other confining units, surface water bodies, and aquifers in the area.

Intra-Bootlegger aquifers

Numerous small sand and gravel units (facies VI-VIII) that can serve as local aquifers for domestic wells have been encountered by wells while drilling through silty BCF deposits. Sometimes drillers note these materials, but the units are too sandy or silty to develop efficiently into water wells and so they drill and case through them into deeper aquifers. Almost all wells in the area (in all formations) are drilled and developed without well screens. Well screens add to the cost of well construction and are usually not necessary because drillers can usually find gravelly deposits that are stable and produce clear water after development through the open end of the well casing/drive shoe.

Figure 10 shows the location of wells that have encountered sand and/or gravel units within the BCF and also denotes wells that are reported to tap these units for water supplies. These wells are not restricted to areas where transition zone or non-cohesive facies (facies VI-VIII) predominate (Ulery and Updike (1983); Figure 5), but numerous such wells are also found east of Jewel Lake Road where cohesive facies (Facies I-V) generally predominate. The elevation of the tops of these units, while shown on Figure 10, are not contoured because the elevations are quite variable and the units are considered small and not generally continuous. Figures 7 and 8 show examples of some intra-bootlegger aquifers in cross section views.

Anchorage confined aquifer system

As previously described, the uppermost sequence of sediments in the eastern part of the project area consists predominantly of silts and clays in the cohesive facies I-V of the BCF. In this area, there are also some deltaic silty fine sand with silt and clay layers and deltaic fine to medium sand with layers of silt and gravel in facies VI and VII of the BCF (Updike and Ulery, 1986; Cross Section C-C'). These deposits overlie stratified glaciofluvial sands and gravels (map unit Qgfo). The sands and gravels are interpreted to be part of the Anchorage confined aquifer system described by Patrick and others (1989) and constitute the primary aquifer system tapped by most wells in the project area.

This study has extended the western boundary of the Anchorage confined aquifer system to include the entire populated area of Sand Lake westward to Jodhpur Street at the west boundary of this study area. In the central and western parts of the study area, the BCF consists of greater amounts of glaciofluvial or deltaic sands and gravels as a result of being closer to the glacial sources of the sediments. Even in these areas, however, significant amounts of silty sediments are found that form local confining layers. At well CLE, for example (drilled in 1987, the year after Updike and Ulery (1986) was published), the well encountered "Gray silty sand - (sticky)" between depths of 160 to 193 feet and "Gray silty sand - water seepage" between depths of 193 to 278 feet below land surface. These deposits are interpreted to be part of the BCF and appear to form a confining or semi-confining layer above the reported "Gray, clean sandy gravel - water bearing" reported between 278-280 feet below land surface. This sand and gravel unit is interpreted to be part of the upper zone of the Anchorage confined aquifer system.

In some places in the western part of the study area (generally in or west of the transition zone shown in Figure 5), sands and gravels of the Bootlegger facies VI-VIII are difficult to distinguish from underlying sands and gravels (map unit Qgfo from Updike and Ulery (1986)) with the available data. In these instances, the BCF sands and gravels are considered to be part of the Anchorage confined aquifer system according to common hydrostratigraphic practice (see, for example, Munk and others (2004), page 14).

Cross Sections A-A' and B-B' (Figures 7 and 8) illustrate that the silty and clayey confining units found in the eastern part of the study area become discontinuous, thinner, and less abundant in the central and western portions of the study area and, generally, undergo a facies change into sandy silts and silty sands. This is consistent with the findings of previous investigators. In the central and western areas, considerable thicknesses of deltaic silty sands are found (see description of well CLE above, for example) that seem to function as semi-confining units, also known as leaky confining units above deeper aquifer zones.

Examination of water well logs and test drilling in the project area have identified the presence of three geographically extensive water-producing zones (the upper, middle, and lower zones) within the Anchorage confined aquifer system in the Sand Lake area. Structure contour maps of the tops of these zones are shown in Figures 11, 12, 13 (and insets). They are also shown in cross sections A-A' and B-B' (Figures 7 and 8).

The existence of multiple sequences of sand and gravel glacioalluvium between silty deposits of till or glaciomarine or lacustrine silts and clays has been previously reported by Schmoll and Barnwell (1984), who recognized five to seven sequences of sand and gravel separated by diamicton and/or glaciolucustrine or glaciomarine silts and clays (pre-BCF). They interpret these sequences as representing sequential glacial advance/retreat cycles. In the Sand Lake area, fine-grained deposits between aquifer zones appear to include till and pre-BCF silts and clays and silty sands although they are mostly not separately distinguished on maps or cross sections.

A well drilled for Dimond High School in 1967 about 1100 feet east of the study area (WELTS Log ID 18644) is an example of what multiple deep aquifer zones in southwest Anchorage are like. This well penetrated six water-bearing layers while drilling to a total depth of 597 feet. This is the deepest water well identified in the area. Relative to mean sea level (well elevation determined from topographic contours from Dearborn and Freethey (1974)), these layer elevations (the tops of the layers) occurred at elevations of -188 feet (21 feet thick), -234 feet (20 feet thick), -323 feet (24 feet thick), -397 feet (11 feet thick), -430 feet (7 feet thick) and -465 feet (25 feet thick). This record of multiple deep aquifer zones separated by confining layers is broadly consistent with the multiple zones of the Anchorage confined aquifer system identified in this report. The Dimond School well also suggests that the lower zone described in this report (and even the deeper zones encountered in the Dimond School well) are likely not the lowest aquifer zones in the area. With 1050 feet of sediments reported to overlie consolidated rock in the former Sand Lake gravel pit (WELTS Log ID 31274; Well_ID Pan-Am, Appendix A), even more and deeper aquifer zones, indicating more cycles of glacial advance and retreat in Cook Inlet, may be present.

Upper zone. Figures 11 and 11a are structure contour maps showing the top of the upper zone of the Anchorage confined aquifer system. This surface closely resembles Figures 6 and 6a , which show the base of the BCF. In some locations, however, the sediments immediately beneath the BCF consist of non-water-yielding diamicton, and are not generally regarded as aquifer material. Most of the wells that encounter the upper zone also tap into it for water supplies. Some wells, however, encountered more silt than drillers desired, which can make well construction and development more expensive, or produced an insufficient amount of water. Some wells (Well_ID CLE, for example) were drilled to be privately-owned public water-supply wells, and required higher yields that prompted the driller to drill deeper looking for a higher-yielding zone. A few wells do not report encountering the upper zone at all, even though they were drilled to a sufficient depth. In some places, the upper zone may be too silty and/or too thin for drillers to have reported it on their logs.

Most wells penetrating the upper zone reported penetrating less than 15 feet of aquifer thickness: only seven wells listed in Appendix A reportedly encounter a thickness of more than 30 feet. Most wells tapping the upper zone penetrated only a few feet into the zone and stopped short of the bottom of the zone.

In the north-central part of the study area and beneath the western part of the South Pond (see Figure 11), the upper zone is inferred to exist under water table conditions.

Middle zone. Figures 12 and 12a are structure contour maps showing the top of the middle zone of the Anchorage confined aquifer system. Like the upper zone, the middle zone appears to be present throughout the study area. The middle zone appears to be approximately 10 to 40 feet thick, although, like the wells tapping the upper zone, many wells were drilled just a few feet into the zone.

Also like the upper zone, a few wells logs do not report encountering the middle zone and were drilled deeper into the lower zone.

Lower zone. Figure 13 is a structure contour map showing the top of the lower zone of the Anchorage confined aquifer system. Although data are sparse and most wells do not report penetrating the bottom of the zone, it appears that the zone is likely approximately 10 to 30 feet thick.

Figures 7 and 8 show two cross sections through the study area that show the relationships of the upper, middle, and lower zones of the Anchorage confined aquifer system.

Aquifer transmissivity and connectivity among zones and aquifers

One of the objectives of this study is to determine approximate groundwater flow directions in the study area and to determine the likely continuity and effectiveness of confining layers and possible connections between aquifers. Munk and others (2003, p. 17) noted that:

> Hydrostratigraphic sequences depicted on ... cross sections are useful for locating areas of higher and lower hydraulic conductivity, however this information cannot be used alone to determine whether or not sands and gravels are hydraulically connected. Hydraulic connectivity is primarily assessed through aquifer tests.

Thus, even the more extensive analysis provided in this report that extends the cross section analysis to a fully three-dimensional stratigraphic analysis is generally insufficient to determine with confidence whether different areas of the groundwater flow system are hydraulically connected or not. For this reason, the aquifer test described in Appendix F was performed. The permeability of aquifer materials and possible connections between different parts of an aquifer are commonly tested by means of conducting aquifer tests.

Dearborn (1983 and Appendix E, Attachment E-1) estimated aquifer transmissivity at a well located in the south part of the former Sand Lake gravel pits (Anchorage Asphalt (AA) well) that penetrates six feet of the upper zone of the confined aquifer system. Based on 11 hours of pumping at 260 gpm with 61 feet of drawdown in the single-well test, a transmissivity value of 1500 ft^2/day was estimated.

TERRASAT, Inc. (2004) pumped the same well in 2004 as a single-well test and estimated the transmissivity of the aquifer to be 1940 ft^2/day.

These estimates can be compared to the estimate by Patrick and others (1989) for the entire thickness of aquifer (approximately 1000 feet, although this includes fine-grained layers that do not contribute significantly to transmissivity). Patrick and others (1989) estimated that the transmissivity of the confined aquifer in the Sand Lake area is in the range of 5,000-10,000 ft^2/day.

Most wells in the Sand Lake area have reported yields at the time of drilling of less than 50 gpm, which would indicate an aquifer transmissivity less than that reported for the Anchorage Asphalt well.

Two test wells drilled adjacent to Westpark Drive near the South Pond (Figure 2) encountered a water table aquifer, a confining unit, and a deeper confined aquifer in the upper zone of the Anchorage confined aquifer system. The deeper well SL-6D, encountered a surprisingly high-yield aquifer. A 24-hour aquifer test was conducted April 28-29, 2016, and described in detail in Appendix F. The test was performed as a step-rate test, with the pumping rate averaging 375 gpm for most of the test. This was the most water that could be pumped by the largest submersible pump that would fit inside the six-inch-diameter well.

The aquifer test analysis indicated that the transmissivity of the aquifer at the site is approximately 22,000 ft^2/day.

Water-level data in monitoring wells collected before, during, and after the test are provided in Appendix E. Small water-level responses that coincided with the initiation of pumping from Well SL-6D, and then to the cessation of pumping 24 hours later, were observed in wells SL-2, KE-22, SL-4D, and SL-4I. The responses were less than 0.5 feet and are characteristic of typical responses in monitoring well during aquifer tests, even though the water levels were also affected by small diurnal fluctuations caused by tidal cycles. No responses to pumping were observed in wells SL-1, KE-21, or SL-6S, although Well KE-21 showed a small rise that may be associated with a rise of the water level in the South Pond, since pumped water was discharged into the pond during the test.

The drawdowns observed in the responding monitoring wells were not considered large enough to warrant a standard quantitative time-drawdown analysis. However, the approximate expected response in the wells based on the method of Theis (1935) was compared to observed responses and found to be reasonably similar, providing confirmation of the aquifer test interpretations.

The results of the aquifer test are somewhat surprising considering the large variation in depth and location of the monitoring wells and the aquifer zones tapped by the wells. The pumped well, SL-6D, is inferred to tap the upper zone. The responses observed in wells tapping the upper zone (KE-22), middle zone (SL-2 and SL-4I) and lower zone (SL-4D) are strong indications that the zones are hydraulically interconnected in the vicinity of the test area. Potential interconnections of these aquifer zones are illustrated in Cross Sections A-A' and B-B' (Figures 7 and 8).

The results of the aquifer test confirm other findings of this investigation that at least some of the individual aquifer zones tapped possess a degree of hydraulic continuity with other zones in the area sufficient to respond to short-term hydraulic stresses. At the SL-6S/SL-6D well site, the confining unit separating the shallow and deeper aquifer is concluded to function as an effective local barrier to short-term hydraulic stresses between the aquifers.

Summary of water-level hydrograph analysis

Historical water-level data collected by the U.S. Geological Survey in the Sand Lake area and hydrographs constructed from pressure transducer-type dataloggers deployed in nine monitoring wells during this study are provided in Appendix E, along with ancillary well data and analysis.

A summary of findings is provided below. Details of the analysis are contained in Appendix E. Historical data show that wells in the Sand Lake area tapping the confined aquifer system (which includes most wells) were influenced by long-term pumping from the aquifer in Anchorage. Up to approximately 20 feet of long-term water-level decline likely occurred, at least in the eastern part of the study area, between about 1955 and the late 1980's when the Eklutna Water Project came on-line and groundwater pumping in Anchorage was reduced. Some wells may have experienced a permanent lowering of water level by up to 5-10 feet as a result of the March 27, 1964, Alaska earthquake (Waller, 1966). Seasonal fluctuations up to 5-10 feet have occurred in some wells, however, these may be largely the result of seasonal variation in pumping from Municipal and other wells. Wells monitored during a one-to two-year period during this investigation showed seasonal fluctuations of less than 2 feet, consistent with observations by Brailey Hydrologic Consultants (2013, 2014, 2015a). Fluctuations in water levels in wells tapping the confined aquifer system before about 1962 seem to be no more than about 3 feet and likely reflect mostly natural conditions. Shallow water-table wells have shown seasonal fluctuations up to about 5 feet.

Four wells tapping the confined aquifer at distances between 1000 and 2000 feet from the pumping well experienced drawdown and recovery water-level responses to an aquifer test conducted April 28-29, 2016. These wells are inferred to tap the upper, middle and lower zones of the confined aquifer system, indicating that hydraulic interconnections exist between the zones.

Several wells also fluctuate diurnally in response to tides, although the response is small, generally less than 0.2 feet in amplitude.

Anchorage currently obtains most of its water from the Eklutna Water Project and groundwater pumpage in Anchorage is greatly reduced from early 1980's levels. Currently, water levels are likely to have returned close to 1950's levels, although data are too sparse to confirm this. This history is why water-level data collected prior to 1964 were used for constructing the potentiometric surface of the confined aquifer system in areas of sparse current (or near-synoptic) water-level data.

Vertical hydraulic gradients. Table 1 shows the results of vertical hydraulic gradient calculations where data are available from closely-spaced wells. Gradients are generally downward, indicating recharging conditions for deeper aquifers. The largest vertical gradient is near the South Pond, as measured at the well pair KE-21/KE-22.

Table 1. Vertical groundwater gradients

Well Pair		Aquifer pair		Comparable water-level elevations and date of measurement[1] (ft MOA72)		Calculated vertical gradient[2]
SL-1	SL-2	Water table	middle zone	39.32 9/14/15	20.92 9/14/15	0.083
SL-3	SL-4I	Water table	upper zone	20.86 6/16/15	20.72 6/16/15	0.0020
SL-4I	SL-4D	upper zone	lower zone	Tidally variable - see Figures E-21 and E-22 (Appendix E)		
SL-5S	SL-5D	Intra-BCF	middle zone	23.19 6/17/15	23.02 6/17/15	0.0017
SL-6S	SL-6D	Water table	upper zone	36.34 5/12/16	18.46 5/12/16	0.11
KE-21	KE-22	Water table	upper zone	39.05 6/17/15	21.15 6/17/15	0.24

Notes:

[1] Data from Appendix A

[2] positive numbers imply downward vertical gradients; calculations used mid-points of open intervals in wells.

Potentiometric surface

One of the objectives of this study is to determine approximate groundwater flow directions in the study area and to ascertain the continuity and effectiveness of confining layers and possible connections between aquifers. One of the methods for accomplishing these goals is the construction of maps of the water table of the unconfined aquifer and also of the potentiometric surface of the confined aquifer system. A potentiometric surface is a contoured surface of the altitudes of water levels in wells that penetrate an aquifer and depict the head in the aquifer.

The potentiometric surface of a confined aquifer is determined by measuring water levels in wells tapping the aquifer and relating the measurements to a common datum, such as MOA 72, to determine the value of hydraulic head in the aquifer. Contours are then drawn based on these values. In a relatively uniform aquifer, groundwater flow directions are then inferred to occur from areas of high head to areas of low head in the aquifer. When multiple aquifers are present, groundwater can flow vertically (either upwards of downwards) from aquifers with higher head to aquifers with lower head through gaps in confining layers or, more slowly, through semi-permeable confining layers. In the Sand Lake area, the discontinuity of confining layers in facies I-V of the BCF in the transitions zone requires careful consideration of aquifer stratigraphy and lateral and vertical gradients of hydraulic head.

A water-level survey was conducted in local wells during May and June 2015, resulting in the construction of a map of the potentiometric surface of the confined aquifer system (Figure 14). Most of the wells used to construct the map were completed in the upper zone of the aquifer, however the data shown in Table 1 and the results of the aquifer test (Appendix F) indicate that the differences in water levels between the different zones of the confined aquifer system are minor. Because the aquifer test (Appendix F) showed that monitoring wells tapping the upper, middle, and lower zones responded to pumping from the upper zone, an examination of the potentiometric surface of the entire confined aquifer system including wells from all zones is considered appropriate. Differences of water levels in wells tapping the different zones are minor, at least where data are available.

In order to provide some data coverage for the eastern and southeastern portions of the map area, selected water-level data from older wells were used. Prior studies have shown that the potentiometric surface in the Sand Lake area has changed since about 1955 as a result of widespread pumping (Moran and Galloway, 2006; Miller and Whitehead, 1999; and Barnwell and others, 1972; Glass, 1987; and Dearborn, 1983). Most of this pumping was by municipal water wells in the years before the Eklutna Water Project began supplying water to Anchorage in the late 1980's. Since water levels in the confined aquifer system in 2015 were likely to have recovered to levels similar to the 1950's, the pre-2015 water levels shown in Figure 14 were mostly collected prior to the early 1960's and are considered to be representative of the largely unperturbed groundwater flow system. Also, the overall range of values in the elevation of the potentiometric surface across the study area of about 70 feet makes small inaccuracies in water levels relatively unimportant.

An important water-level measurement for constructing Figure 14 was collected at well SL-6D, which was drilled in 2016 following the completion of the 2015 water-level survey. The water-level elevation shown in Figure 14 from that well was adjusted upward by 0.32 feet because the water levels measured in Wells KE-22, SL-2, and SL-5 were all 0.32 feet lower at about the same time in 2016 as they were during the 2015 water-level survey.

Figure 14 shows the potentiometric surface and inferred directions of groundwater flow in the confined aquifer system. The map generally shows groundwater flow from the east towards the former Sand Lake gravel pits, where contouring suggests that flow turns towards the south and the coastal bluffs. There is an apparent local groundwater divide from the location of SL-5S and SL-5D that trends northward to the Lucy Street Fill Site area. This unusual flow configuration suggests that there is an aquifer of higher transmissivity located east of this divide that has the effect of draining water southwards towards the coast. This interpretation is consistent with the interpretation of the aquifer test data showing the presence of an aquifer of unusually high transmissivity in this area. The possible existence of a high transmissivity aquifer in that vicinity was also suggested by Brailey (2015a): "The southeastward flow direction at the Lucy Pit could be a result of deep aquifer recharge to the north (Figure 2-2), or highly transmissive aquifer with a coastal discharge area to the south."

This report also shows that there is a small but persistent downward gradient from the water table aquifer to the upper zone of the confined aquifer system in the vicinity of wells SL-3, SL-4I, and SL-4D. This means that the most likely explanation for the anomalous water-table gradient found by Brailey Hydrologic Consultants (2013, 2014, 2015a) is that flow from the water table aquifer leaks downward and recharges the confined aquifer system in the vicinity of the platted location of 80th Avenue on the east side of Lucy Street and Well_ID ASG4 (Figures 9 and 9a - water-table contour maps) where a closed contour (a depression in the water table surface) of 20 feet elevation exists. Such a closed contour generally indicates that groundwater flows toward the center of the area enclosed by contour, usually to a pumping well where water is removed from the aquifer. In this case, there is no pumping well in that area and water is inferred to leak out of the aquifer downward to the upper zone of the confined aquifer system.

Aquifer recharge

Many prior authors have noted that recharge to the Anchorage confined aquifer system occurs in the foothills of the Chugach Mountain front on the east side of Anchorage. In the study area, the general trend of the potentiometric surface from east to west indicates that groundwater flow enters the study area from the east, in conformance with the foothills recharge conceptual model. If the transmissivity of the aquifer (along the east side of the study area) is approximately 5,000 - 10,000 ft^2/day as estimated by Patrick and others (1989), and the gradient of the potentiometric surface is approximately 0.005 as seen on Figure 14, then the amount of groundwater flow entering the east side of the study area would be approximately 250,000 to 500,000 cu ft/day using a standard Darcy's Law calculation (Freeze and Cherry, 1979).

Patrick and others (1989) also estimated that approximately four inches of groundwater recharge occurs annually in the Sand Lake area. Applying this amount of recharge to the study area equates to an average of approximately 120,000 cu ft/day of groundwater recharge. Thus, it can be seen that local recharge likely comprises a significant percentage of recharge to local aquifers. These calculations are consistent with several observed phenomena that indicate local groundwater recharge:

- downward vertical gradients that occur throughout most of the study area (see Table 1);
- the closed contour "mounds" in the water table;
- the closed or nearly closed contour "mounds" or "ridges" in the potentiometric surface;
- the closed contour depression in the water table contour map near Lucy Street that implies recharge from the water table aquifer to the upper zone of the confined aquifer system; and
- Sand Lake, Sundi Lake, and Jewel Lake are perched above the local water table, implying that there is likely some amount of downward vertical leakage from the lakes to the water table and deeper aquifers;
- the almost complete absence of streams in the study area suggests that runoff is low and groundwater recharge is widespread in the study area, especially in areas underlain by permeable soils such as the former Sand Lake gravel pits.

Groundwater quality and geochemistry

Measurements of common dissolved minerals in groundwater in the Sand Lake area show that the general quality is good, although about half of wells sampled exceed the Maximum Contaminant Level (MCL) for arsenic that is applicable to public water supplies. There is no MCL applicable to single-family domestic water well supplies in Anchorage.

Water from seven wells (three monitoring wells and four domestic wells) exceed the secondary MCL of 500 mg/L for total dissolved solids. Measured values were up to 880 mg/L. Secondary MCLs are not health-related and indicate possible aesthetic conditions such as taste, scaling, or staining. Numerous wells also exceeded the secondary MCLs for iron and manganese. One well reportedly (Municipality of Anchorage data - see nitrates section below) exceeded the MCL for nitrate nitrogen that is applicable to public water supplies. Water quality data are presented in Appendix B.

The overall geochemistry of the groundwaters in the Sand Lake area analyzed for this study indicate that the water is dominantly calcium bicarbonate or calcium-magnesium bicarbonate-type water, which is typical for Alaskan groundwaters derived from unconsolidated aquifers (Miller and Whitehead, 1999). Figure 15 is a Piper plot illustrating the overall geochemical composition of the waters in all of the neighborhoods investigated in this study. Appendix G provides detailed Piper plots for the sub-areas shown in Figure 15.

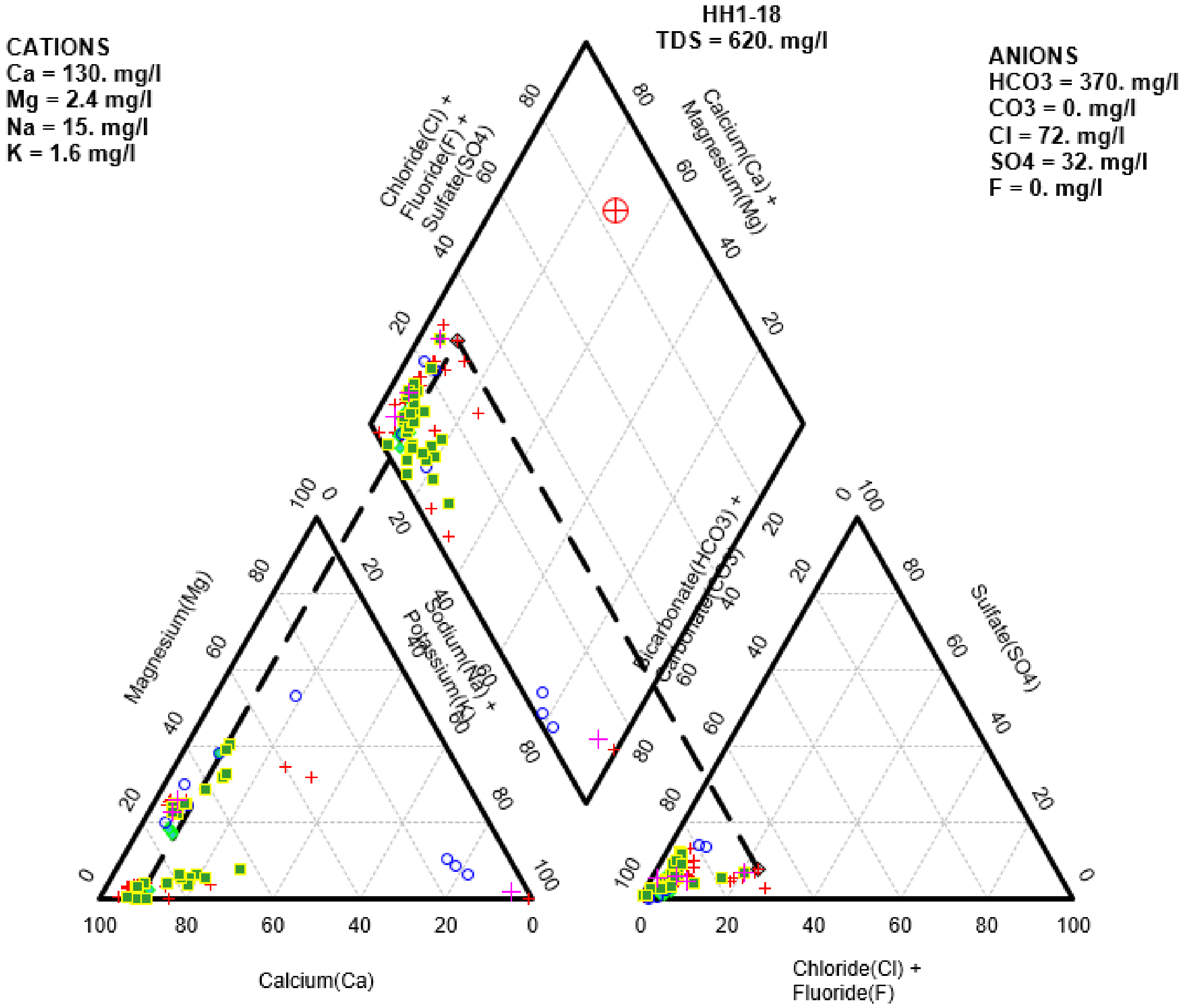


Figure 15. Piper plot for all waters analyzed. Red plus signs are Hidden Hills, blue circles are Sand Lake #2, green/yellow squares are Seaview Heights, green diamonds are Kincaid Estates and pink crosses are Tanaina Hills. Dashed black line shows an example of how to read the

Piper plot combining the cations and anions onto the diamond plot and the overall geochemical composition and TDS is listed for that example.

The water quality analyses exhibit some variation across the study area and with wells of different depths. This is generally consistent with Kane and others (2008), who noted differences in a number of different cations and ions across the study area. Seasonal water quality differences were found to be minor.

Arsenic

Arsenic is generally regarded as a naturally occurring element in groundwater in the Anchorage area. There are no obvious anthropogenic sources of arsenic known, such as mines, agricultural chemicals, or wood preservatives that would account for the distribution of arsenic found during this and prior studies.

Arsenic is an element found in the mineral arsenopyrite, which is found associated with quartz veining in the rocks forming the Chugach Mountains. Arsenic is also commonly associated with coal (https://pubs.usgs.gov/fs/2005/3152/), which is noted in numerous well logs as detrital coal in the area (see, for example, Munk and others, 2010, Figure 2).

Prior investigators have noted the existence of elevated levels of arsenic in more than half of wells sampled in wells in the Sand Lake area (Municipality of Anchorage, 2004; Kane and others, 2008). The geochemistry of arsenic in Anchorage groundwater was investigated by Munk and others (2011). Additional information about arsenic in Anchorage groundwater is available at: http://www.muni.org/Departments/health/Admin/environment/AirQ/Pages/ArsenicIndex.aspx.

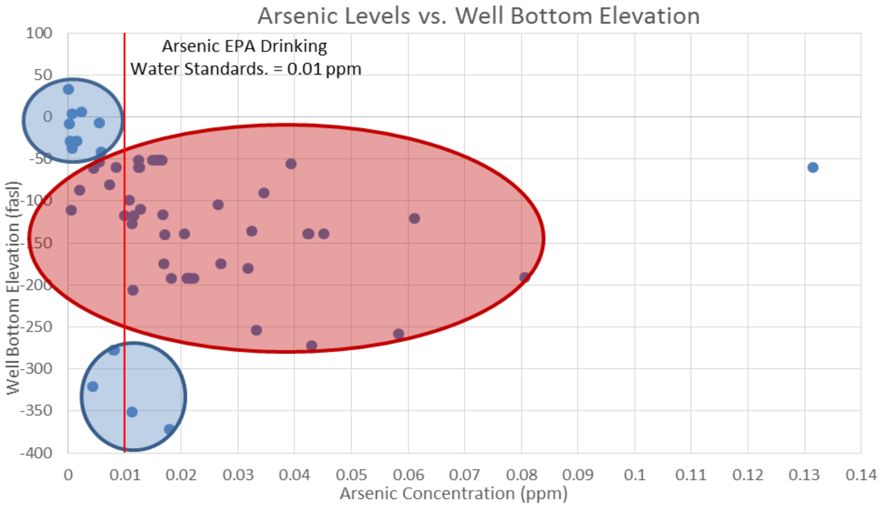


Figure 16. Arsenic concentrations for all well water sampled during this study.

Figure 16 shows arsenic concentrations for all well water analyses collected during this study. The mid-level well depths have the most variable arsenic concentrations but also show that the highest arsenic concentrations occur in water from these well depths. The EPA maximum contaminant level applicable to regulated public water supplies is 0.01 ppm. Approximately 65% of wells sampled exceeded this standard, somewhat less than the findings of Kane and others (2008), who found that 86% of their sampled well exceeded the standard. The Municipality of Anchorage, which regulates single-family domestic wells in Anchorage, does not have a maximum contaminant level for arsenic.

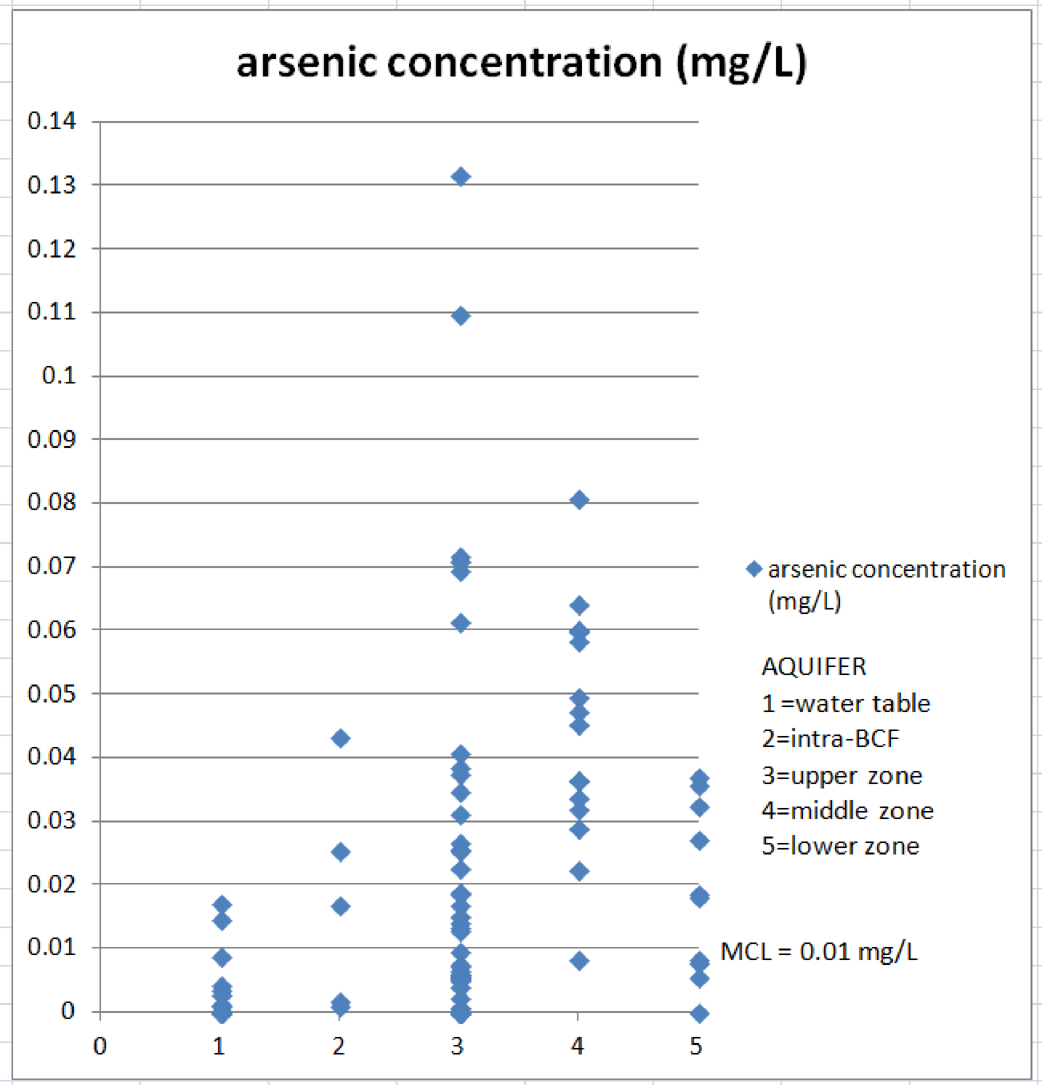


Figure 17. Arsenic concentrations sorted by aquifer tapped.

Figure 17 is a plot of arsenic data from wells sampled during this project as well as data collected by Kane and others (2008) and some data from Municipality of Anchorage On-Site records. In general, the On-Site program requires that arsenic data be submitted when a health authority approval is requested as part of new construction or a home sale.

The data in Figure 17 are differentiated by aquifer and zone. The data shown in Figure 17 show a similar pattern to that seen in Figure 16, with the highest concentrations of arsenic observed in the upper zone (or mid-depth wells), with lowest values from wells tapping the shallower water-table and deeper lower zone aquifers. The data used for Figure 17 only used the highest value of arsenic per well, if multiple values were available. Also, when arsenic concentrations were less than detection limits (generally 0.005 mg/L or less), a value of zero was plotted. These data indicates that if a well with elevated arsenic concentrations taps the upper zone, the well could potentially be deepened or redrilled to tap a lower zone and may obtain water with lower concentrations of arsenic.

Figure 18 shows the spatial distribution of arsenic in well water from samples collected during this study and by Kane and others (2008) and some reported data from Municipality of Anchorage On-Site records. The values shown are the highest value, if multiple samples were analyzed. Map symbols with any color other than green represent well water with elevated levels of arsenic that tested above the MCL for arsenic of 0.010 mg/L. The highest concentrations of wells with elevated levels of arsenic are generally in the central part of the study area. In wells that were tested multiple times for arsenic, the values were usually relatively consistent (see Appendix B).

Nitrates

The Municipality of Anchorage maintains a publically-available web-based map of nitrate data collected from wells in Anchorage and reported to the On-Site program as part of the health authority approval process. These data, while commonly referred to as "nitrates", are alternatively described in Appendix B of this report as nitrate-nitrogen, to distinguish them from data reported in other places as nitrate ion concentrations. Nitrate ions contain three oxygen molecules that changes the molecular weight compared to nitrate nitrogen (and thus the reported concentration in mg/L), but not the number of nitrogen ions in the sample.

Figure 19 shows that nitrate values are generally low in the study area, although higher values are found in the Kincaid Acres and Hidden Hills subdivisions. The primary MCL for nitrate-nitrogen applicable to public water supplies is 10 mg/L. The Municipality of Anchorage, which regulates single-family and duplex wells, does not have a regulatory MCL for nitrate-nitrogen. The Municipality of Anchorage's web-based map can be found at: https://muniorg.maps.arcgis.com/apps/webappviewer/index.html?id=6c3acc5dca8244a891f954f0e7f75496.

Nitrate data collected as part of this project and contained in Appendix B generally follows the patterns described above.

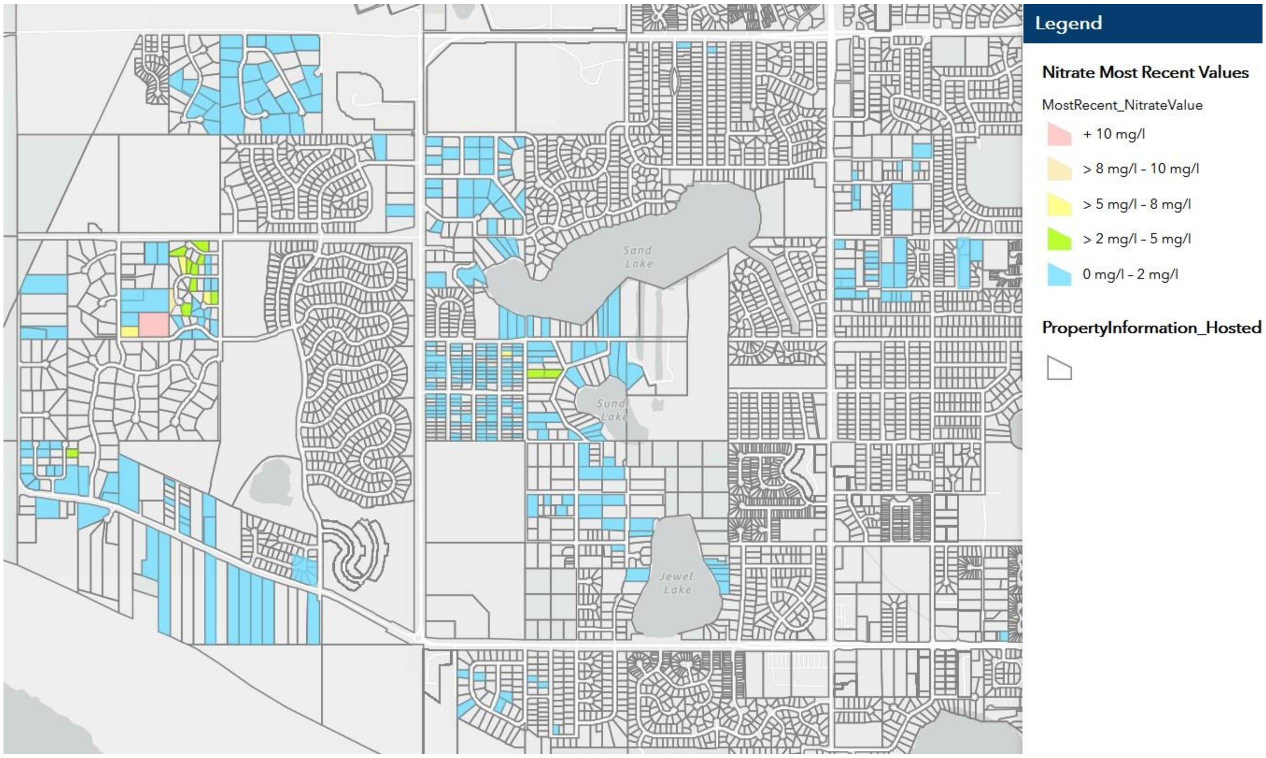


Figure 19. Reported nitrate concentrations (from Municipality of Anchorage https://muniorg.maps.arcgis.com/apps/webappviewer/index.html?id=6c3acc5dca8244a891f954f0e7f75496, accessed May 5, 2021)

AQUIFER SUSCEPTIBILITY AND VULNERABILITY TO CONTAMINATION

The susceptibility of an aquifer to contamination is defined as "the inherent ability of a formation to accept and transmit liquids (potentially including contaminants)" (https://en.wikipedia.org/wiki/Aquifer_Susceptibility). A susceptible aquifer becomes a vulnerable aquifer when one or more potential source of contamination are present that could result in groundwater contamination.

In the Sand Lake study area, eastern areas underlain by locally continuous layers of fine-grained facies of the Bootlegger Cove Formation are relatively protected from contamination. In the western part of the study area, no continuous confining layers are present and the aquifer zones tapped by many wells are relatively susceptible to contamination. In the transition zone, local protection of the aquifer by effective confining layers may occur, but there is also the potential for gaps and discontinuities of confining layers that could provide pathways for contaminants.

There are a wide variety of anthropogenic activities in the Sand Lake area that have had the potential to contaminate groundwater. These include:

- gas stations;
- dry cleaners;

- Lucy pit and Sand Lake pit fill structures;
- septic systems,
- animal (mainly dog) waste,
- urban stormwater runoff.

The Alaska Department of Environmental Conservation maintains a database and map-searchable inventory of closed and active contaminated sites (https://www.arcgis.com/home/webmap/viewer.html?webmap=315240bfbaf84aa0b8272ad1cef3cad3). Numerous sites are located immediately north of the project area at the former Kulis Air National Guard base.

A site-by-site assessment of potential source of contamination is beyond the scope of this investigation, however throughout the course of this project, no drinking water wells are alleged to have been contaminated by human activities except the Dodds and Shantz wells described in Appendix H. Reports of sediments travelling from the South Pond to those two wells have been extensively reviewed and analyzed in Appendix H of this report. The analysis found that:

> All data reviewed during this investigation indicates that the Dodds (2003) claim that the excavation of the South Pond in 1978 directly caused turbid water to flow through the aquifer and into their well and household plumbing system is plausible and is the most likely explanation for what happened. All alternate explanations or opinions by other investigators have been examined and rejected for multiple reasons, leaving no other viable working hypothesis to explain the observed facts

This study confirms the finding of Munk and others (2010) that aquifers in the area of the South Pond "appear to be susceptible to surface contamination and that efforts to avoid or minimize future contamination of these aquifers are warranted."

Considerable effort has been spent since 2015 about how to deal with urban stormwater generated in the former Sand Lake gravel pits and nearby areas. This stormwater has no natural outlet to a stream or to the coast, so when Westpark Subdivision was developed, a piped discharge system was constructed under Dimond Boulevard to discharge to the coast. This system was determined to be undersized to handle current project stormwater runoff (Municipality of Anchorage, 2019) and a storm-drain overflow structure was constructed in 2016 that has twice discharged urban storm-water runoff into the South Pond.

This has been of concern to area residents because of the perceived vulnerability of the aquifer beneath the pond, and because urban stormwater runoff in Anchorage is known to carry contaminants such as petroleum hydrocarbons, metals, antifreeze, nutrients, pesticides, herbicides, bacteria, and viruses. These compounds come from automotive wastes, pesticide and herbicide applications, lawn fertilizing, and animal (largely dog) residues (Municipality of Anchorage, 2014). Chemical compounds from rubber tires can also contaminate stormwater runoff. Approximately 2000 such chemical compounds exist. It has recently been found, for example, that one such compound, 6PPD-quinone is responsible for mysterious die-offs of adult Coho salmon along the U.S. west coast (University of Washington, 2020).

Recent efforts to reroute the overflow storm drain to discharge into a bioswale (Municipality of Anchorage, 2019) to minimize or avoid discharging stormwater directly into the South Pond would be more protective of surface and groundwater quality than the existing stormwater overflow structure.

SUMMARY AND CONCLUSIONS

This report presents a comprehensive analysis of groundwater occurrence and movement in the Sand Lake area, a largely residential area of southwest Anchorage. Hundreds of homes in this area rely on individual wells for water supply. Re-development of old gravel pits during the past 19 years has resulted in concerns of impacts to water quality from urban stormwater discharge into a pond created by gravel mining and two areas where former pits have been filled.

This study uses well logs from over 300 wells to map a discontinuous confining layer in the area, the Bootlegger Cove Formation, and the tops of three underlying zones of the Anchorage confined aquifer system. In addition, a near-synoptic water-level survey is used to map the water table and the potentiometric surface of the confined aquifer system, which provides an indication of the directions of groundwater flow. Groundwater generally flows towards Cook Inlet, although apparent connections between aquifers are inferred that influence local flow directions.

A 24-hour high-flow aquifer test was conducted to identify connections between different aquifers and zones. It demonstrated that confining units are discontinuous within a 2000-ft radius of the pumping well.

The quality of water is generally suitable for domestic use except that approximately half of wells sampled exhibited concentrations of arsenic that exceeded requirements applicable to public water-supply wells.

Circumstances surrounding two wells that were reported to have been contaminated by fine sediment flowing through the aquifer at the time the South Pond was dug in 1978 were investigated. It was found that there are no other viable explanations for the events. A review of the literature of sediment transport in groundwater, a geological pathway analysis, a hydraulic gradient analysis, and Darcy' Law calculations of travel time all indicate that the transport of sediment from the pond to the wells was plausible, and that this explanation is the most likely explanation for the observed facts. This finding is relevant to ongoing efforts to protect the quality of groundwater used for water supply in the area, showing the importance of ongoing groundwater protection efforts.

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Files that are also part of this report:

FIGURES (that are not embedded in the text)
(file names are provided in *italics*)

Figures 2, 2a, 2b, 2c, 2d, 2e, 2f, and 2g. Locations of wells used for this study (and Insets): *Figure 2 Well Location Maps.pdf*
Figure 3. Locations of wells sampled during this study: *Figures 3 6 9-14 18.pdf*
Figures 6. Structure contour map of the base of the Bootlegger Cove Formation (BCF) and
Figures 6a. Sand Lake and Sundi Lake Inset: *Figures 3 6 9-14 18.pdf*
Figure 7. Cross section A-A': *Figure 7 Cross Section A-A'*
Figure 8. Cross Section B-B' *Figure 8 Cross Section B-B'*
Figure 9. Water table contour map and
Figure 9a. Lucy Street Inset: *Figures 3 6 9-14 18.pdf*
Figures 10. Locations of wells reportedly encountering Intra-Bootlegger aquifers: *Figures 3 6 9-14 18.pdf*
Figure 11. Structure contour maps of the top of the upper zone of the Anchorage confined aquifer system and
Figure 11a. Sand Lake and Sundi Lake Inset. *Figures 3 6 9-14 18.pdf*
Figures 12. Structure contour maps of the top of the middle zone of the Anchorage confined aquifer system and
Figure 12a. Sand Lake and Sundi Lake Inset. *Figures 3 6 9-14 18.pdf*
Figure 13. Structure contour map of the top of the lower zone of the Anchorage confined aquifer system: *Figures 3 6 9-14 18.pdf*
Figure 14. Potentiometric surface of the Anchorage confined aquifer system. *Figures 3 6 9-14 18.pdf*
Figure 18. Arsenic concentrations from wells sampled by this study, Kane and others (2008) and reported by Municipality of Anchorage: *Figures 3 6 9-14 18.pdf*

APPENDICES
(file names are provided in *italics*)

Appendix A. Well data: *Appendix A Well data*

Appendix B. Water quality data: *Appendix B Water quality data*

Appendix C. Test Well logs: *Appendix C Test well logs*

Appendix D. Geophysical Investigation: *Appendix D Sand Lake Geophysics final 10192015*

Appendix E. Hydrographs and analysis of water-level data**:** *Appendix E Water level data*
Appendix E Attachment: *Attachment E-1 Dearborn 1983 AA well report*

Appendix F. Aquifer test analysis: *Appendix F Aquifer test analysis*
  Appendix F Attachment: *Attachment F-1 Time-drawdown plot and results of aquifer test analysis*

Appendix G. Additional water quality plots: *Appendix G Piper plots by area details*

Appendix H. The wells of Loren and Betty Dodds and Dan Shantz and particle transport analysis in groundwater: *Appendix H Particle Transport Analysis*
  Appendix H Attachment: *Attachments H1 - H8*