Susitna-Watana Hydroelectric Project
(FERC No. 14241)

Groundwater Study
Study Plan Section 7.5

2014-2015 Study Implementation Report

Appendix C

Summary Review of Susitna River Hydrogeologic Studies Conducted in the 1980s with Relevance to Proposed Susitna-Watana Dam Project and other Non-Project Related Studies

Prepared for

Alaska Energy Authority

SUSITNA-WATANA HYDRO

Clean, reliable energy for the next 100 years.

Prepared by

Pacific Groundwater Group

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LIST OF ACRONYMS AND SCIENTIFIC LABELS

Abbreviation	Definition
2-D	two-dimensional
Acres	Acres American, Inc.
AEA	Alaska Energy Authority
APA	Alaska Power Authority
ARLIS	Alaska Resources Library and Information Services
bgs	below ground surface
cfs	cubic feet per second
EIS	Environmental Impact Statement
FERC	Federal Energy Regulatory Commission
ft	Foot
ft/d	Feet per day, unit of hydraulic conductivity
ft^2/d	Feet squared per day, unit of transmissivity
GIS	Geographic information system
GW	Groundwater
IfSAR	Interferometric Synthetic Aperture Radar
ISR	Initial Study Report
LiDAR	Light Detection and Ranging
LR	Lower Susitna River Segment
MR	Middle Susitna River Segment
PRM	Project River Mile
Project	Susitna-Watana Hydroelectric Project, FERC No. 14241
R&M	R&M Consultants, Inc.
RSP	Revised Study Plan
SW	Surface Water
UR	Upper Susitna River Segment
USGS	United States Geological Survey
WCC	Woodward-Clyde Consultants

1. INTRODUCTION

On December 14, 2012, Alaska Energy Authority (AEA) filed with the Federal Energy Regulatory Commission (FERC) its Revised Study Plan (RSP) to support the federal licensing process of the Susitna-Watana Hydroelectric Project, FERC No. 14241 (Project). The RSP included 58 individual study plans (AEA 2012). Included within the RSP was the Groundwater Study, Section 7.5 RSP Section 7.5 focuses on providing an overall understanding of groundwater (GW)/surface water (SW) interactions at both the watershed and local scales. This understanding will be used in evaluating Project operational effects on GW/SW interactions and resulting effects on riparian and aquatic habitats.

Operation of the Project is expected to change the hydrologic characteristics of the riverine portion of the drainage downstream of the proposed Watana dam and the mainstem Susitna River reach inundated by the Project reservoir. Project operations will cause seasonal, daily, and hourly changes in Susitna River flows compared to existing conditions. The potential alteration in flows will influence downstream resources/processes, including fish and aquatic biota and their habitats, channel form and function including sediment transport, water quality, GW/SW interactions, ice dynamics, and riparian and wildlife communities.

This memo focuses on the first of the nine objectives identified in RSP Section 7.5.1, which is to synthesize historical and contemporary GW data available for the Susitna River GW and GW dependent aquatic and floodplain habitat, including that from the 1980s and other studies including reviews of GW/SW interactions in cold regions. This literature review focuses on the characterization of data and information for the following five hydrogeologic concepts and properties that are important for understanding GW/SW interactions within the Susitna River:

- Aquifer extent and thickness
- Aquifer properties (transmissivity, hydraulic conductivity, and storage)
- Horizontal GW gradients and flow direction
- Nature and extent of vertical GW gradients along the Susitna River
- Groundwater and SW interactions within the Susitna River valley

The synthesis of these hydrogeologic properties is intended to provide a summary of previous (pre-2012) Susitna hydroelectric project studies and other non-Project related studies relating to the dynamics and characteristics of GW near the Susitna River. Recent Project studies in some instances are referred to, but were not the focus of this review.

2. STUDY AREA

As established by RSP Section 7.5.3, the study area related to GW processes includes primarily the Middle Susitna River Segment (MR) of the Susitna River that extends from Project River Mile (PRM) 102.4 to PRM 187.1 as well as portions of the Lower Susitna River Segment (LR) associated with domestic wells and riparian transect locations in the LR, and the lowest portion of the Upper Susitna River Segment (UR) near the proposed Watana dam site associated with potential GW changes relative to reservoir construction and operations. Figure 1 shows these river segments and the general watershed boundary of the Susitna River. Figure 2 shows the location of the ten Focus Areas within which detailed studies are being conducted. These are described in Initial Study Report (ISR) Study 8.5, Section 4.2.1.2.1.

Most documents examined as part of this literature review have focused on the MR; the UR and LR have less available GW related data.

3. METHODS

The Alaska Resources Library and Information Services (ARLIS) database was queried for reports for the Susitna River prior to the current study. The terms Susitna hydrogeology, geohydrology, hydrology, geology, and ice were searched, with the subject terms chosen with the intent of identifying reports likely to contain data relating to the five hydrogeologic concepts/properties identified in Section 1. A total of 278 document matches were obtained from ARLIS, and documents that were electronically available and had potentially relevant titles were downloaded. Report table of contents were then reviewed to assess if relevant hydrogeologic data were likely present in the report. If relevant data appeared to be present, sections of the report with hydrogeologic data were reviewed. In some instances older reports were superseded by younger reports (as in the case of draft and final reports, or seasonal/single year data reports versus multi-year reports with an overlapping timespan), and in these cases the more recent reports were reviewed. Though generally not summarized in this literature review, some recent (2012 or newer) GW and geologic Project reports were briefly reviewed, and if useful non-Project related sources were cited (in recent reports or 1980s reports), these reports were obtained via internet search.

The information obtained from these reports is expected to benefit current and future GW studies by compiling existing hydrogeologic data (or reference to it) within one document, yielding gains in efficiency and potentially highlighting previous studies that current authors may be unaware of.

4. SUMMARY OF DOCUMENTS REVIEWED

The following 17 documents were identified during the literature review as containing important and relevant information to the ongoing GW Study (Study 7.5) and were therefore reviewed for hydrogeologic information relevant to the Susitna River. These are presented in chronological order. Twelve of the documents contain findings of project studies conducted during the 1980s.

Acres American, Inc. (Acres). 1980. Susitna Hydroelectric Project, Subtask 6.01 Closeout Report, Design Development, Review of Previous Studies and Reports. Report prepared for the Alaska Power Authority (APA). December 1980. APA Document No. 1275. ***http://www.arlis.org/docs/vol1/Susitna/12/APA1275.pdf***

This report is a literature review summarizing previous dam siting studies and proposed dam locations along the Susitna River. Available geotechnical data were briefly described with riverbed sediment thicknesses reported for Devil Canyon[1] (near PRM 153), Watana (PRM 187.1), and Vee (near PRM 224).

Acres American, Inc. (Acres). 1982. Susitna Hydroelectric Project, 1980-81 Geotechnical Report, Volume 1, Final Draft Report prepared for the Alaska Power Authority. APA Document No. 69. ***http://www.arlis.org/docs/vol1/Susitna/0/APA69.pdf***

This report presents geotechnical data collected in the vicinity of the Watana dam site from 1980 to 1981. Presented geotechnical data relevant to hydrogeology include alluvial thicknesses, bedrock hydraulic conductivity values, and grainsize analysis data (which can be used to estimate hydraulic conductivity for sediments that are predominantly sandy). Detailed geologic mapping (at 1:6000 scale), geologic cross-sections, and numerous borehole logs are also presented.

Trihey, W.E. 1982. 1982 Winter Temperature Study, Open File Report. Prepared for Acres American, Inc. SUS Document No. 158. June 1982. ***http://www.arlis.org/docs/vol1/Susitna/SUS/1/SUS158.pdf***

This report presents results from an early study examining slough water and intergravel water temperatures during the winter of 1982. Several MR sloughs were instrumented for this study, including Sloughs 8A, 9, 9B, 11, 19, 20, 21, and 21A. Numerous data plots with mean daily temperatures for sloughs and slough intergravel water are presented.

R&M Consultants, Inc. (R&M). 1982. Susitna Hydroelectric Project Slough Hydrology Interim Report. Water Balance Studies of Middle Susitna Sloughs. Prepared under contract with Acres American Inc. for the Alaska Power Authority. December 1982. ***http://www.arlis.org/docs/vol2/hydropower/APA_DOC_no._438.pdf***

This study focused mostly on Slough 8A and 9 with the intent of describing flow regimes and origins of the GW component of slough discharge. Sloughs 8A and 9 were chosen as study sites based on previous observations of GW input to the sloughs, and their relatively easy access from the Alaska Railroad. Slough 8A is located at PRM 128.7, while Slough 9 is approximately located at PRM 131.5.

A total of 15 wells were installed at or near Slough 9, while 12 wells were installed in or near Slough 8A. These wells were installed with a backhoe, with the wells installed only slightly below the water table due to caving conditions. In the Slough 9B region four additional wells were installed with a drill rig, which allowed the wells to extend significantly below the water table. Data presented in this report include well logs, a detailed cross-section tracing the Slough 9 thalweg profile in relation to mainstem water elevations for varying conditions (including winter open channel flow and winter ice cover flow), and a comparison of aerial photos from

[1] All 1980s reports referred to this area and the proposed dam for this canyon as "Devil" (not Devils) Canyon, so "Devil" is referred to throughout this document.

1951 and 1980 is presented for Sloughs 8A, 9, and 11. Additionally, locations of GW upwelling in Sloughs 8A and 9 were mapped and are shown in Figures 3 and 4 of this report.

The following analyses were performed in an effort to estimate GW contribution to Sloughs 8A and 9B (with Slough 9B shown in Figure 4): measuring SW inflows and outflows from Slough 9, measuring the seepage rate from the bank of Slough 9B, measuring GW elevations to calculate horizontal GW gradients and travel times, and sampling isotopic tracers to assess if unique and traceable signatures were present from different water sources. Temperature data were also collected and presented, but were analyzed via a model in the Acres (1983) report discussed below.

Acres American, Inc. (Acres). 1983. Draft, Susitna Hydroelectric Project, Slough Hydrogeology Report. Report prepared for the Alaska Power Authority. APA Document No. 519. March 1983. ***http://www.arlis.org/docs/vol1/Susitna/5/APA519.pdf***

The objective of this study was to understand slough hydrogeology under natural conditions in an effort to provide a methodology to predict post-dam conditions. It bases its analysis and conclusions on field data collected from Sloughs 8A and 9 as reported in the December 1982 Interim Slough Hydrogeology Report (R&M 1982). Data collected in 1982 was used to develop a two-dimensional (2-D) finite-element GW flow model and a temperature transport model for Slough 9.

Modeled GW flow reasonably matched observed flow for the mainstem, which is downvalley with local lateral flow to Slough 9. The report concludes that GW dispersion and heat exchange between water and sediments is a reasonable mechanism to account for near-constant upwelling temperatures in Slough 9.

A discussion of expected downstream flow conditions during the construction, filling, and operation of the Watana and Devil Canyon dams is also presented, with focus on both the mainstem and the sloughs.

Harza-Ebasco. 1983. Susitna Hydroelectric Project, Watana Development, Winter 1983 Geotechnical Explorations Program, Volume 1, Main Report. Prepared for the Alaska Power Authority, September 1983. APA Document No. 374. ***http://www.arlis.org/docs/vol1/Susitna/3/APA374.pdf***.

Geotechnical data collected during the winter of 1983 and interpretations are presented in this report for the Watana dam site area. Relevant hydrogeologic parameters presented include sediment thicknesses, measured bedrock and sediment hydraulic conductivities, and grainsize analysis data (which can be used to estimate hydraulic conductivity for sandy sediments). Bedrock elevation contours, bedrock channel widths, geologic cross-sections, and numerous borehole logs are also presented.

Harza-Ebasco. 1984a. Susitna Hydroelectric Project, Slough Geohydrology Studies. Prepared in cooperation with R&M Consultants, Inc. for the Alaska Power Authority. APA Document No. 1718. April 1984. ***http://www.arlis.org/docs/vol1/Susitna/17/APA1718.pdf***.

This report reviews much of the available hydraulic and thermal data (from the early 1980s) for side sloughs on the MR between Devil Canyon and Talkeetna. Based on review of these data, it was concluded that due to the uniqueness and hydraulic complexity of each slough, it is not possible to formulate a single conceptual model applicable to all sloughs. This observation lead them to conclude it was not possible at the time to quantitatively predict changes in slough temperature or discharge due to changes in mainstem conditions tied to dam operations.

Sloughs 8A, 9, 11, and 21 were the primary areas of focus for the study, with presented data including aquifer test data from the Talkeetna area, GW level and temperature measurements from wells near Sloughs 8 and 9, SW elevation and discharge data, seepage meter data from the sloughs, SW temperature data, and climatic data. Estimates of GW flow in the alluvium beneath the MR were made, and concluded that large proportions of slough discharge are likely tied to shallow lateral flow from the mainstem or local runoff rather than regional GW underflow within the Susitna River valley-fill materials. Predictive ratios of slough discharge to mainstem discharge were presented. Groundwater discharge from the valley wall material was also estimated, and found to be minimal. Additionally, some basic GW and temperature modeling was performed to investigate the rate at which changes in mainstem stage or temperature would likely propagate through GW to the sloughs. The qualitative effects of dam operation on downstream sloughs is also discussed.

Harza-Ebasco. 1984b. Susitna Hydroelectric Project, 1984 Geotechnical Exploration Program, Watana Dam Site, Main Report. Prepared for the Alaska Power Authority April. APA Document No. 1734. July 1984. ***http://www.arlis.org/docs/vol1/Susitna/17/APA1734.pdf***.

Geotechnical data collected in 1984 near the Watana dam site are summarized in this study. A brief discussion of GW elevations and flow in bedrock is presented, as well as hydraulic conductivity test results for bedrock and overlying sediments. Other hydrogeologically-relevant data presented include geologic cross-sections, borehole logs, water level data plots, and grain size analysis data.

Alaska Power Authority (APA). 1984. Alaska Power Authority Comments on the Federal Energy Regulatory Commission Draft Environmental Impact Statement of May 1984, Volume 9, Appendix VII - Slough Geohydrology Studies. APA Document No. 1780. August 1984. ***http://www.arlis.org/docs/vol1/Susitna/17/APA1780.pdf***.

This study appendix is part of the APA's comments on the FERC draft Environmental Impact Statement (EIS) of May 1984, and represents the most updated analysis (to its publication date) of slough hydrogeology based on 1980s data. Much of this report is similar to Slough Geohydrology Studies report (Harza-Ebasco 1984a), but new interpretations, analyses, and explanations of the data are also interspersed. Other studies not evaluated in prior slough hydrogeology reports (including temperature modeling results and various fish studies) are integrated into the interpretations and analyses.

New analyses presented within this report include expected monthly GW upwelling rates for Slough 11 with and without dam operations is projected, predicted Slough 9 upwelling temperatures under dam operating conditions, and predictions that more stable upwelling flows and temperatures will occur in sloughs due to less fluctuation in mainstem Susitna discharges and temperatures. The report concludes that existing data were insufficient to make a complete evaluation of the possible sources of GW upwelling to the sloughs, and that extensive drilling and aquifer testing would be necessary for this evaluation.

R&M Consultants, Inc. (R&M) 1985. Water Balance Studies of Middle Susitna Sloughs, Final Report. Prepared under contract with Harza-Ebasco Susitna Joint Venture for the Alaska Power Authority June. APA Document No. 2745. June 1985. ***http://www.arlis.org/docs/vol2/hydropower/APA_DOC_no._2745.pdf***.

Rainfall and runoff data collected in 1984 was analyzed in this report using a water mass balance approach. These analyses lead to the conclusion that GW flow into a slough is related to the stage of the mainstem, with alluvial gradients controlled by the mainstem stage. Regression relationships were developed for Sloughs 8A, 9, and 11 to predict slough flow based on mainstem flow for periods when the upstream slough berms are not overtopped by the mainstem. Groundwater sourced from the uplands of a slough watershed was also found to be a significant source of water for some sloughs, with its relative impact dependent on soil depths within the watershed (with deeper soils preventing rapid runoff and resulting in more GW recharge). The study concludes that the examination of watershed characteristics can suggest how sloughs without significant hydrologic data will react to changes in mainstem flow.

Additional hydrologic data collection which occurred as part of this study included aquifer tests on five wells in Slough 9, the installation of additional stream gauging stations, and the installation of additional precipitation gages.

R&M Consultants, Inc. (R&M) and Woodward-Clyde Consultants (WCC). 1985. Instream Flow Relationships Report Series, Physical Processes of the Middle Susitna River, Technical Report No. 2, Final Report. Prepared under contract with Harza-Ebasco Susitna Joint Venture for the Alaska Power Authority. APA Document No. 2828. June 1985. ***http://www.arlis.org/docs/vol1/Susitna/28/APA2828.pdf***.

The purpose of this report series was to identify the relative importance of interactions between primary physical and biological components of the MR aquatic habitat. Data presented in the report were generated in a variety of baseline studies, with hydrogeologically relevant data including river stages at different reaches for different discharges as measured at the United States Geological Survey (USGS) Gold Creek stream gage; grain size analysis data for slough beds (which may be used to estimate hydraulic conductivity); a stratigraphic explanation of river upwelling zones; and a hydrograph plotting Slough 8A, 9, 11, and mainstem flows in response to a storm event.

This report concludes that because of the substantial differences among sloughs in the hydraulic and thermal behavior, detailed projections of slough discharge or temperature variations relative to mainstem conditions could only be made if mathematical models are constructed for each individual slough. Additional field investigations would also be necessary to generate input data for the models, and it is expected that different sloughs will have different discharge responses to with-project conditions.

Seagren, D.R, and R.G. Wilkey. 1985. Summary of Water Temperature and Substrate Data from Selected Salmon Spawning and Groundwater Upwelling Sites in the Middle Susitna River, Technical Data Report No. 12. Alaska Department of Fish and Game, Susitna River Aquatic Studies Program. December 1985. ***http://www.arlis.org/docs/vol1/Susitna/29/APA2913.pdf***.

This technical data report presents a summary of surface and intergravel water temperature and substrate composition data collected at selected salmon spawning and GW upwelling sites in the MR. Data presented in this report were collected during the open-water (July 1 to October 15, 1984) and ice-covered (November 1, 1984 to April 25, 1985) sampling periods. The study focused on open leads (defined as linear breaks in ice cover where open water is present in winter) and known salmon spawning areas. Open leads are considered to be indicators of thermal influences resulting from the presence of GW upwelling or high water velocities.

Of the 52 side channel sites that were surveyed during the open-water season, GW upwelling or bank seepage was observed at 29 side channels, 39 side channels had open leads during winter, four sites had GW upwelling and no open leads in winter, and 15 sites exhibited open leads in the winter but had no visible upwelling.

Of the 25 mainstem sites that were surveyed during the open-water season, 11 had GW upwelling or bank seepage, 16 of the sites had open leads during winter, three sites had GW upwelling and no open leads in winter, and eight sites exhibited open leads during the winter but had no visible upwelling.

Surface and intergravel water data were collected for each ice-covered study site, with mean daily intergravel and SW temperatures summarized in boxplots. Areas of open leads with no spawning had the warmest intergravel and SW temperatures during the main ice covered period and the warming period prior to spring breakup, which indicates that water temperature does not appear to be a limiting factor for salmon spawning for all sites.

Wilson, F.H., J.H. Dover, D.C. Bradley, F.R. Weber, T.K. Bundtzen, and P.J. Haeussler. 1998. Geologic Map of Central (Interior) Alaska Southeastern Region. U.S. Geological Survey Open-File Report 98-133.

This 1:500,000-scale geologic map presents surficial geologic units from the Susitna River watershed. The map primarily focuses on bedrock geology and faults, with all quaternary sediments mapped as a single unit. Bedrock units adjacent to the MR of the Susitna River include the Kahiltna Flysch Sequence of sedimentary rocks from the late Cretaceous to late Jurrasic (KJf), granitic rocks from the Paleocene (Tpgr), and gneissose granitic rocks (TKgg) from the early Tertiary to the early Cretaceous. The KJf formation is described as deformed, tightly isoclinally folded, and complexly faulted, while the crystalline units Tpgr and TKgg describe no faulting or deformation. In most areas, Quaternary sediments are present between the MR and valley sidewalls, except for geomorphic reaches MR-3 and MR-4 (Figure 2) which have little to no alluvial sediments present and are underlain by Tpgr and TKgg through the Devil Canyon area.

Geologic units in close proximity to the LR of the Susitna River are mapped as Quaternary sediments. Geologic units in close proximity to the UR are primarily Quaternary sediments, though some areas include bedrock. Several thrust faults are also crossed by the UR.

Penn Jersey Drilling Inc. 2007. Daily Drilling Logs and Water Flow Test Data for Alaska Railroad Corporation.

Well logs from Curry (where two wells were installed in 2007 at depths of 120 and 112 feet) were reviewed since they are the deepest known wells adjacent to the MR segment. Well 2 at Curry (the 112 foot well) had step drawdown test and recovery data which was reviewed and analyzed. Curry is approximately located at PRM 123.

Wilson, F.H., C.P. Hults, H.R. Schmoll, P.J. Haeussler, J.M. Schmidt, L.A. Yehle, and K.A. Labay. 2009. Preliminary Geologic Map of the Cook Inlet Region, Alaska. U.S. Geological Survey Open-File Report 2009-1108.

This 1:250,000-scale geologic map presents surficial geologic units from the LR of the Susitna River segment and extends into the lowermost section of the MR. Quaternary sediments were mapped as multiple different units, creating a significantly more detailed geologic map than 1998 map for Central Alaska.

Primary geologic units mapped in the LR floodplain include: Qgc (glacial alluvium from the Upper Pleistocene); Qsl (lacustrine, swamp, and fine silt deposits from the Quaternary); Qat (alluvium along major rivers and in terraces from the Holocene); Qg (major moraines and kame deposits from the Upper Pleistocene); Qgo (outwash in plains/valley terrain and alluvial fans from the Upper Pleistocene); and Qge (glacioestuary deposits from the Upper Pleistocene located near Cook Inlet).

U.S. Geological Survey (USGS). 2013. Shallow Groundwater in the Matanuska-Susitna Valley, Alaska – Conceptualization and Simulation of Flow. Scientific Investigations Report 2013-5049.

This study characterized the geology of the Matanuska-Susitna valley and created a 3-dimensional GW flow model to simulate shallow GW flow. The primary Focus Area from this model was to the south and east of the Little Susitna River (or from Houston to Palmer, Alaska), with very few data points near the LR. The western edge of the model domain includes the LR, which was used as a boundary condition for defining the GW flow direction beneath the land between the LR and the Little Susitna River.

While the LR was not the focus of this report, water level and recharge maps were developed for the eastern half of the LR basin as part of this work, and are shown in Figures 5 and 6. Since model calibration did not focus on this region of the model, simulated flow maps and hydraulic properties (recharge and hydraulic conductivity) used within the model for the LR area should be considered estimates for this area due to the lack of available data.

Lepain, D.L, R.G. Stanley, N.T. Harun, K.P. Helmold, and R.M. Tsigonis. 2015. Reconnaissance Stratigraphic Studies in the Susitna Basin, Alaska, During the 2014 Field Season. in Gillis, R.J. (ed),2015. Overview of 2014 Energy-Focused Studies in Susitna Basin, South-Central Alaska, and Preliminary Results. Alaska Division of Geological and Geophysical Surveys, PIR 2015-3.

This study presents observations and findings of field investigations regarding the source, reservoir, and seal potential of various sedimentary rocks in the Susitna Basin west of Talkeetna. Since the report did not focus on hydrogeology and since all study locations are distant from the LR, information from this report has not been interweaved into this literature review.

5. AQUIFER EXTENT AND THICKNESS

Regional geologic maps for the Susitna watershed were reviewed (Wilson et al. 1998; Wilson et al. 2009) to understand the nature and extent of geologic formations and aquifers that may potentially affect the Susitna River. Aquifer thickness was examined by reviewing existing reports and interpretations, and in some cases by reviewing existing well logs.

5.1. Hydrogeologic Setting and Conceptual Model

The following discussion of hydrogeologic setting is summarized from existing project studies, primarily Harza-Ebasco 1984a; R&M 1985; and AEA 2014 (ISR Study 4.5).

Unconsolidated fluvial and glaciofluvial deposits occur within a very narrow interval along the Susitna River valley. The sloughs and mainstem of the river are part of the modern floodplain. Floodplain deposits are characterized as a mixture of cobbles, sand, and gravels with silty mantles. It is probable that the floodplain alluvium has variable hydraulic conductivities both vertically and laterally, reflecting movement of the stream bed location during sediment deposition (Acres 1983). Above and adjacent to the valley floodplain lie a series of fluvial and glaciofluvial terraces deposited during the most recent Pleistocene glaciations and as the Susitna River re-established its channel and grade following the glaciations. The terrace deposits typically consist of coarse sandy gravels overlain by a few feet of sandy silt or silt overbank deposits. Alluvial fan deposits have formed on the floodplain and adjacent terraces where tributary streams have deposited sediments on these surfaces (R&M 1982). Older unconsolidated glacial deposits may underlie the terrace and floodplain deposits. Collectively the floodplain deposits and any underlying unconsolidated sediments are referred to as the alluvial aquifer in this report.

The uplands adjacent to the floodplain are composed of bedrock consisting of Mesozoic sedimentary rocks of the Kahiltna assemblage and Cenozoic granitic rocks. The bedrock also underlies the alluvial aquifer at a typically unknown depth. In some locations (the Watana dam site, Gold Creek, and Devil Canyon) alluvial thicknesses are defined (ranging from 35 to 140 feet thick), but in general its thickness is poorly defined and expected to vary as a function of underlying bedrock topography and surficial deposition processes. Groundwater and SW monitoring from nearly all monitored MR sloughs indicate that the alluvial aquifer is in hydraulic connection with the Susitna River along with its associated side-channels and sloughs.

Groundwater elevations and vertical gradients show a strong response to changes in river stages at most locations in the modern floodplain.

Groundwater recharge to the alluvial aquifer is derived from four potential sources:

- Direct infiltrating precipitation (rain and snow melt)
- Local to regional GW underflow within the alluvial aquifer that is transported in the downstream direction of the Susitna River valley
- Regional GW transported through the deeper bedrock towards the alluvial aquifer within the Susitna River valley
- Seepage of SW from the Susitna River, side channels, and sloughs (i.e., downwelling in losing reaches)

Groundwater discharge from the alluvial aquifer is predominantly towards the Susitna River and associated side channels and sloughs (upwelling). Areas of GW upwelling in side channels and sloughs create favorable conditions for aquatic habitat by providing warmer water during the critical winter months. Areas of GW upwelling and downwelling are driven by the magnitude, direction and duration of vertical hydraulic gradients between the river SW stage and GW in the underlying aquifer. Areas of upwelling and downwelling are highly variable spatially and seasonally, and are strongly dependent on river stage and aquifer response. It is hypothesized that local upwelling zones are controlled by “piping zones” where semi-confined conditions exist (due to the presence of fine silt layers that locally exist above and below highly permeable sand and gravel deposits) that allow for rapid responses to mainstem stage changes in slough upwelling zones (R&M and WCC 1985).

5.2. Middle Susitna River Segment Aquifer Extent and Thickness

The alluvial aquifer underlying much of the MR of the Susitna River likely has varying thicknesses and widths at different locations. Previous reports have assumed that the aquifer is 100 feet thick and 3,000 feet wide (including the active channel and floodplain) based on review of aerial photos between Slough 8A and 11 (Harza-Ebasco 1984a).

A review of geologic maps for the area suggests that unconsolidated sediments on the valley floor are 2 to 3 miles wide for most of the MR, with the exception of near Talkeetna (where the valley is wider) and near Devil Canyon, where the river is narrowly incised through bedrock and very little alluvial sediment is present. ISR Study 6.5, Appendix A, Study Component 1, Submitted to the FERC June 3, 2014 (Tetra Tech 2014a) plots the river relative to the mapped geology of Central Alaska (Wilson et al. 1998); however, since this map is a regional-scale map with a 1:500,000 scale, exact geologic contacts and valley sediment extents are likely inaccurate since many of these features were not mapped to the slough Focus Area scale.

Average valley bottom widths were recently evaluated for individual geomorphic reaches based on 2011 Light Detection and Radar (LiDAR), 2010 Interferometric Synthetic Aperture Radar (IfSAR), and Geographic Information System (GIS) analysis, with the valley bottom defined as being 20 feet vertically above the water surface elevation at the time of the LiDAR survey (Geomorphic Reach Delineation and Characterization, Upper, Middle, and Lower Susitna River

Segments, Technical Memorandum submitted to the FERC May 27, 2014 [Tetra Tech 2014b]). These widths are potentially the most accurate values for the alluvial aquifer lateral extent, and ranged from 370 feet (at Devil Canyon) to 8,960 feet (by Talkeetna).

Few measured sediment depths exist for the MR, with the total alluvial thickness averaging 80 feet at the Watana dam site (Harza-Ebasco 1983), 100 feet at the Gold Creek railway bridge abutments (R&M and WCC 1985), and 35 feet in Devil Canyon (Acres 1980). In other locations the thickness of the alluvial aquifer is undefined, but is documented to be at least 120 feet deep near Curry (at approximately PRM of 123, [Penn Jersey Drilling 2007]); at least 100 feet deep at the Talkeetna Fire Hall (Harza-Ebasco, 1984a); and at least 43 feet at Slough 9B (R&M 1982). As found upstream of the Watana dam site and discussed in the following subsection, sediment thicknesses are expected to vary as a function of the underlying bedrock topography and depositional processes, and may differ substantially (by 30 or 40 feet) over the course of a few hundred feet (Harza-Ebasco 1983).

5.3. Upper and Lower Susitna Aquifer Extent and Thickness

Aquifer extent and thickness data were only located in geotechnical documents relating to the Watana dam site for the UR of the Susitna River. At the Watana dam site, the alluvial aquifer width is roughly 430 feet, and its across-valley thickness ranges from roughly 65 to 95 feet, with an average thickness of roughly 80 feet as shown in Figure 7 (Harza-Ebasco, 1983). Within 1,000 feet upstream of the dam site, an alluvial aquifer thickness of up to 140 feet was found in a bedrock depression, which suggests that along the bedrock-bound sections of the UR and MR the alluvial aquifer thickness can vary significantly and is dependent on bedrock topography and depositional processes.

Valley bottom widths for the UR (as defined in Tetra Tech 2014a, and discussed above) range from 555 feet to 1,200 feet, which are likely similar to the width of the UR alluvial aquifer.

Minimal aquifer extent and thickness data were located in the documents reviewed for the LR. The USGS GW model report for the Matanuska-Susitna valley (USGS 2013) included the east bank of the LR, though this data for this region of the model was limited. Based on maps presented in this report, the estimated thickness for the shallow unconsolidated aquifer near the LR is approximately 250 to 400 feet thick. Valley bottom widths (Tetra Tech 2014b) ranged from 4,000 to 31,000 feet. The LR valley is primarily composed of quaternary sediments, with few bedrock outcrops present to limit the extent of sediments. The broad extent of sediments in the LR valley suggests that the aquifer underlying the Susitna River transitions from a relatively localized aquifer bounded by bedrock to a much larger regional aquifer system.

6. AQUIFER PROPERTIES

Aquifer properties used in existing reports fall into two categories, assumed or estimated values (due to lack of data) and calculated values based on local measurements. The following subsections present values obtained by both methods, and a general discussion of the applicability of local aquifer properties being applied to distant areas. Aquifer properties are tabulated in Table 1.

6.1. Assumed or Estimated Transmissivity, Hydraulic Conductivity, and Storage Coefficient

Due to limited well and aquifer test data, aquifer properties were estimated in several prior analyses.

6.1.1. Valley Wall Characteristics

The 1984 Slough Geohydrology Report (Harza-Ebasco 1984a) estimated discharge from valley walls using an assumed hydraulic conductivity of 0.014 ft/d and an assumed saturated thickness of 500 feet, yielding a transmissivity of 7.1 ft^2/day. A storage coefficient value was not estimated.

6.1.2. Susitna River Alluvial Characteristics

The 1984 Slough Geohydrology Report (Harza-Ebasco 1984a) estimated GW underflow beneath the MR using an assumed horizontal hydraulic conductivity of 67 ft/d and an assumed saturated thickness of 100 feet, yielding a transmissivity of 6,700 ft^2/d. Additionally, this report presented hydraulic conductivity values for wells near Talkeetna and within half a mile of the Susitna River. Of the six wells presented, five of them were shallow (ranging from 16 – 26 feet deep) and had transmissivities estimated based on well specific capacities (the ratio of pumping rate to water level drawdown). A pumping test was performed on the sixth well, and is discussed in the next subsection. The transmissivities estimated from the site capacities ranged from 334 to 1,070 ft^2/d, while the horizontal hydraulic conductivities ranged from 22 to 133 ft/d, with a mean horizontal hydraulic conductivity of 57 ft/d.

The 1984 Slough Geohydrology Report (Harza-Ebasco 1984a) assumed a storage coefficient of 0.0002 for confined aquifers and 0.2 for unconfined river sediments.

The 1983 Slough Hydrogeology Report (Acres 1983) presented a hydraulic conductivity value of 170 ft/d based on grain size analysis (which frequently results in high bias), and cited data from a study in Fairbanks where a hydraulic conductivity of 1,000 ft/d was estimated. Based on this range of values, a hydraulic conductivity of 200 ft/d was assumed for analysis, and a transmissivity of 9,000 ft^2/d for Slough 9. A storage coefficient of 0.18 was assumed for the modeling analysis presented in the report.

The 1982 Slough Hydrology Interim Report (R&M 1982) presented a hydraulic conductivity value of 226 ft/d based on grain size analysis (which is likely biased high), and cited data from a study in Fairbanks where a hydraulic conductivity of 1,000 ft/d was measured.

The 2013 USGS Modeling report for the Matanuska-Susitna Valley (USGS 2013) simulated GW flow adjacent to the LR. Calibrated horizontal hydraulic conductivity values for these sediments ranged from 16.9 to 19.3 ft/d. The calibrated vertical hydraulic conductivity for LR riverbed sediments was 1 ft/d.

6.2. Calculated Local Aquifer Properties

6.2.1. Valley Wall Characteristics

Geotechnical reports for bedrock near the proposed Watana and Devil Canyon dams presented bedrock hydraulic conductivities ranging from 1.4 to 0.0003 ft/d (Acres 1981; Harza-Ebasco 1983; Harza-Ebasco 1984b). Valley wall sedimentary deposits had measured hydraulic conductivities ranging from 0.9 to 0.09 ft/d (Harza-Ebasco 1984b). Assumed hydraulic conductivity values used for estimating valley wall discharge (reported Section 6.1.1) fall within this range, but may potentially under- or over-estimate valley wall discharge volumes for local sloughs.

6.2.2. Susitna River Alluvial Characteristics

The 1983 Winter Geotechnical Exploration Report (Harza-Ebasco 1983) measured hydraulic conductivity values for alluvial sediments with gravelly sand and sand textures near the Watana dam site. Coarser-grained gravel and sandy gravel sediments could not be measured due to equipment limitations. Measured horizontal hydraulic conductivity values ranged from 4 to 340 ft/d. Given that only finer grained alluvial sediments were measured, this report concluded that alluvial materials are generally very pervious.

The 1984 Slough Geohydrology Report (Harza-Ebasco 1984a) included a hydraulic conductivity value for the Talkeetna Fire Hall well based on 29-hours of pumping and water level drawdown data. The calculated horizontal hydraulic conductivity was 84 ft/d, with a transmissivity of 1858 ft^2/d. The sediments tested in this well were from 78 to 100 feet below ground surface (bgs), and therefore may not be representative of the shallow/uppermost sediments underlying the Susitna River. In the 1984 report this well was interpreted as being confined; however, its static water level (30 feet bgs) is similar to the depth where water was first encountered during drilling (between 18 and 47 feet), and therefore an alternative interpretation could be that the well is unconfined and has a saturated thickness of 70 feet, which would result in a calculated transmissivity of 5,900 ft^2/d.

The 1985 Water Balance report for the MR (R&M 1985) presents aquifer test results for five wells near Slough 9, which yielded transmissivities ranging from 0.2 to 92 ft^2/d and hydraulic conductivities ranging from 0.15 to 31 ft/d.

Data presented with the 2007 Curry well logs include step-rate drawdown test data for Curry Well 2 (Penn Jersey Drilling 2007). Though these data were found to be noisy, data analysis was possible and PGG calculated a hydraulic conductivity of approximately 123 ft/d and a transmissivity of 7,600 ft^2/d.

Other existing data that could be analyzed to yield approximate hydraulic conductivity values are the seepage meter data presented in the 1984 Slough Geohydrology Report (Harza-Ebasco 1984a) Appendix F. These data include seepage rates at Sloughs 8A, 9, 11, and 21, head values (in some cases) relative to the slough water level for piezometers installed next to the seepage meter, slough water levels, and a description of seepage meter construction (the end of a 55 gallon drum with an attached bladder). It should be possible to estimate bank hydraulic conductivities using Darcy's Law with the provided data, the diameter of a 55 gallon drum, an assumed standard piezometer intake depth (1 foot below substrate was reported for a piezometer in Slough 8A, no other piezometers had documented depths), and a slough water depth (which could either be calculated or estimated from stage data and staff gage descriptions in Appendix E of the document).

Additional data that has not been analyzed but could yield hydraulic conductivity estimates include grain size analysis data for slough beds (R&M and WCC 1985), river alluvium (Harza-Ebasco 1983), and terrace/till deposits (Acres 1982; Harza-Ebasco 1983; R&M and WCC 1985).

Though local hydraulic conductivity values have been documented at some locations along the MR, it is an extremely variable parameter and commonly can differ by factors of 10 or 100 for measurements taken within similar materials in close proximity to one another. Therefore the application of local hydraulic conductivity values from one slough to another is generally not recommended, and values applied from other sloughs should be considered rough estimates at best.

Since no data from pumping tests with one or more observation wells were presented in the reviewed reports, direct calculation of aquifer storage properties is not possible. Typical storage coefficient values for unconfined aquifers range from 0.01 to 0.3 while typical values for confined aquifers are much less and range from 0.005 to 0.00005 (Freeze and Cherry 1979).

7. HORIZONTAL GROUNDWATER GRADIENTS AND FLOW DIRECTION

Horizontal GW gradients and flow directions for sloughs 8A and 9 in the MR are well documented and are temporally variable. Local to regional-scale GW flow beneath the MR via the subsurface alluvial aquifer is poorly mapped, but likely occurs down-valley parallel to the river, with local flow near valley walls oriented toward the river. Gradients and flow directions beneath the MR will be discussed in the following subsection.

Horizontal GW flow near the LR segment is poorly defined due to a lack of data, but has been simulated by the USGS as documented in the Matanuska-Susitna valley modeling report (USGS 2013). A map of simulated GW flow for the east bank of the LR is reproduced in Figure 6. The simulated hydraulic gradients depicted in Figure 6 range from approximately 0.004 to 0.006 ft/ft.

Horizontal GW flow and gradients in the UR segment are poorly defined and no reviewed documents presented data for this area. For areas with unmapped GW flow paths and gradients, GW flow will likely follow topography on hillslopes outside of the floodplain, while within the alluvial aquifer flow will generally be oriented downstream or toward the river.

7.1. Middle Susitna Groundwater Gradients and Flow Direction

Groundwater elevation maps presented in the 1984 Slough Geohydrology Report (Harza-Ebasco, 1984a) and 1983 Slough Hydrogeology Report (Acres 1983) present GW flow maps largely based on data reported in the 1982 Slough Hydrology Interim Report (R&M 1982). The 1982 report presents multiple water elevation map snap shots, with data from Slough 8A including one map from April 1982, six from September to October 1982, and one from December 1982 under ice jam conditions. At slough 8A, GW generally flows downstream, but can have more significant lateral components of flow away from the mainstem during high flows or when high heads are induced at the mainstem by ice staging and/or ice dams. The diversion of the mainstem through the slough during ice dam conditions can also result in significant GW flow toward the mainstem. An example GW flow map for Slough 8A from the 1982 report is reproduced in Figure 8.

Groundwater contour maps for Slough 9 from 1982 include single maps for water level snapshots in April, May, June, and December, and maps for two separate dates in July, September, and October. At Slough 9, GW generally flows downstream, with Slough 9B consistently gaining except for during ice jam events. Groundwater flow from valley sidewalls appears to play a role near Slough 9, where GW flow consistently has a component of flow toward the river rather than solely downstream (with the exception of during an ice jam event). An example GW flow map for Slough 9 from the 1982 report is reproduced in Figure 9.

In general, measured horizontal hydraulic gradients from 1982 near Sloughs 8A and 9 were roughly 0.0022 to 0.0033 ft/ft, with gradients varying temporally based on seasonality and mainstem river conditions.

8. NATURE AND EXTENT OF VERTICAL GROUNDWATER GRADIENTS ALONG THE SUSITNA RIVER

None of the reports reviewed had “nested” well completions (where wells with different screen depths are completed within a few feet of one another), and therefore no measurements of the vertical hydraulic gradient in GW alone exist. Vertical gradients may be calculated in locations where wells are installed immediately adjacent to a SW body, but in general some separation exists between the reviewed wells and/or SW bodies, which introduces a component of horizontal hydraulic gradient into the measured differences, and therefore purely vertical gradients cannot be calculated.

Seepage meter data presented in Appendix F of the 1984 Slough Geohydrology Report (Harza-Ebasco 1984a) could be used to approximate vertical gradients for Sloughs 8A, 9, 11, and 21, though the exact construction details for each piezometer installed next to the seepage meters and the ponded water depths at the piezometers may be sources of uncertainty in the vertical gradient estimates.

Inferences regarding vertical hydraulic gradients (direction and magnitude), however, can be made based on well, slough, and mainstem water level hydrographs, with hydrographs providing a clear visual characterization of when gradients change. Historic reports that contain such data include R&M 1985 and Harza-Ebasco 1984a.

No vertical hydraulic gradient data were available for the UR and LR segments. In general, for all segments of the Susitna River, vertical hydraulic gradients are expected to typically be upward since the Susitna River is a large regional river draining a roughly 20,000 square mile basin, and therefore regional GW flow paths are expected to converge and upwell at the river.

Losing or downwelling conditions may seasonally occur during flows associated with the summer snowmelt (when the river stage could be higher than local GW elevations), during short-term high flow (storm) events, or possibly where changes in geology occur (such as where a transition from a bedrock stream bed to an alluvial stream bed occurs).

9. GROUNDWATER-SURFACE WATER INTERACTIONS

Groundwater and SW (GW/SW) interactions have been studied for numerous sloughs in the MR, but no studies were found for the LR and UR. A significant confounding variable in the analysis of SW/GW interactions on the MR is that when a slough's berm is overtopped by the mainstem (due to either high summer flows or lower flows associated with ice damming), flow from the main river enters the slough and dominates the slough flow regime. The durations of these events can be short (such as a storm event response) or weeks to months (in the case of diversions tied to an ice dam or high summer flows tied to headwater snowmelt).

GW/SW interactions along the MR have historically been investigated through multiple means, which have included water level maps (R&M 1982), maps of upwelling areas (R&M 1982), stable isotope ratios (R&M 1982), a 2-D GW flow model (Acres 1983), temperature modeling (Acres 1983), GW modeling to simulate head variations in a stream-aquifer system (Harza-Ebasco 1984a), discharge hydrograph comparisons (Harza-Ebasco 1984a), regression lines relating slough and mainstem discharge (Harza-Ebasco 1984a; R&M 1985), regression lines relating seepage rate to mainstem discharge (Harza-Ebasco 1984a), comparative analysis of temperatures in sloughs, wells, and the mainstem (Harza-Ebasco 1984a), comparing observed or simulated GW levels to mainstem stage (Harza-Ebasco 1984a; R&M 1985), and comparing slough discharge to mainstem discharge (R&M 1985). As evident by the variety of field studies and analyses performed to characterize SW/GW interactions, the quantification and characterization of SW/GW interactions is difficult due to the spatial and/or temporal variability of the multiple driving variables (which include the mainstem river stage, slough stage, geologic materials, slough morphology, ice conditions, and runoff response). Based on these variabilities, the 1980s reports concluded that individual regression equations or relationships defined between any given slough and the main stem could not be applied generally across the MR.

In recent studies, models of SW hydraulics (Open-water Flow Routing Model [Study 8.5]); SRH-2D hydraulic model (Study 6.6), ice processes (River1D and River2D [Study 7.6]), and 3-dimensional GW flow (MODFLOW [Study 7.5]) have been developed, and when coupled should be able to quantify changes in GW discharge to sloughs based on varying mainstem conditions. These model results when linked with the 2-D PHABSIM Fish Habitat models (Study 8.5) will be able to assess the likely impacts of dam operations on fish and aquatic habitats within selected Focus Areas.

The following subsections summarize quantitative GW/SW interaction data from the 1980s reports.

9.1. Slough 8A Groundwater-Surface Water Interactions

Slough 8A was one of the primary sloughs studied in the 1980s[2], with the following study findings for GW/SW interactions:

- R&M Consultants (1982): This report identifies the mainstem discharge rate for overtopping Slough 8A as 26,000 cubic feet per second (cfs) for the northwest channel and 30,000 cfs for the upstream channel (with flow rates measured at Gold Creek). Figure 10 is a map from this report showing the locations of the controlling berms. Oxygen-18 and deuterium samples were also collected from the Susitna River and at different locations in Slough 8A, and isotope sampling was identified as a possible mechanism to separate GW and SW flows based on different isotopic signatures. Given that the slough flow regime and Susitna River isotope ratios are expected to vary seasonally or more frequently, frequent isotope sampling would be required to evaluate the flow regime for variable conditions.

- Harza-Ebasco (1984a): This report qualitatively notes that significant amounts of precipitation can be absorbed in the Slough 8A basin following long dry periods, but a rapid runoff response can occur in larger events. From September 28 – October 3, 1983 the estimated slough baseflow was 1.5 cfs, which was approximately 10 percent of the total discharge from the slough over this period. Regression equations relating Slough 8A discharge versus mainstem discharge were developed, and found that if multiple high flow outliers were removed, a coefficient of determination (r^2) of 0.632 could be obtained. Based on this regression equation, the change in slough discharge relative to mainstem discharge can be estimated for certain time periods by multiplying the mainstem discharge by 0.0001. Two seepage meters were also installed in Slough 8A, with seepage rates from both meters positively correlated with mainstem discharge.

- R&M Consultants (1985): This report identifies the mainstem discharge rate for overtopping Slough 8A as 27,000 cfs for the northwest channel and 33,000 cfs for the upstream channel. It is unclear if the change in reported overtopping discharges relative to 1982 is due to changes in stream morphology, or if it reflects a larger dataset with more precise overtopping discharge rates. From monthly water balances performed between July and October of 1984, it is calculated that 62 to 73 percent of precipitation that fell formed runoff. Linear and logarithmic relationships between mainstem and slough discharge were found when the upstream berm of the slough is not overtopped, with r^2 values ranging from 0.53 to 0.91.

9.2. Slough 9 Groundwater-Surface Water Interactions

Slough 9 was the most studied slough in the 1980s, with the following study findings for GW/SW interactions:

[2] Slough 8A is likewise being intensively investigated as part of the ongoing Susitna-Watana studies and is designated as Focus Area (FA)-128 (Study 8.5).

- R&M Consultants (1982): This report identifies the mainstem discharge rate for overtopping Slough 9 is 23,000 cfs at Gold Creek. Figure 11 is a map from this report showing the location of the controlling berm. When the Slough 9 berm is not overtopped, slough flow is derived from surface runoff via small streams and GW inflow. The percent of flow derived from surface runoff and from GW is quantified in one daily snapshot from August 1982 and one daily snapshot form September 1982, with the ratios varying due to antecedent precipitation. Oxygen-18 and deuterium samples were also collected from the Susitna River and at different locations in Slough 9, and isotope sampling was identified as a possible mechanism to separate GW and SW flows based on different isotopic signatures. Given that the slough flow regime and Susitna River isotope ratios are expected to vary seasonally or more frequently, frequent isotope sampling would be required to evaluate the flow regime for variable conditions.

- Acres American (1983): Groundwater flow and thermal modeling of Slough 9 were conducted to assess if GW upwelling in Slough 9 could be derived from the Susitna River (since the upwelling GW has a nearly constant temperature). Based on thermal dispersion and dampening, it was concluded that the Susitna River could be the source of the near-constant temperature water discharging in the slough. However, though not noted in the report, based on the isotopic mixing data presented in R&M Consultants (1982), it is unlikely that all of the upwelling water originates from the Susitna River (unless isotopic ratios from the river vary significantly through the year).

- Harza-Ebasco (1984a): This report qualitatively notes that a rapid runoff response occurs in the Slough 9 basin. From September 28 – October 3, 1983 the estimated slough baseflow was 5.73 cfs, which was approximately 48 percent of the total discharge from the slough over this period. Regression equations relating Slough 9 discharge versus mainstem discharge were developed, and found that if high mainstem flows (> 16,000 cfs at Gold Creek, which was when the berm would overtop in 1984) were excluded, a coefficient of determination (r^2) of 0.805 could be obtained. Based on this regression equation, the change in slough discharge relative to mainstem discharge can be estimated for certain time periods by multiplying the mainstem discharge by 0.00035. Three seepage meters were also installed in Slough 9, with the seepage rate from one meter positively correlated with mainstem discharge, while the other two did not appear correlated to mainstem discharge.

- R&M Consultants (1985): This report identifies the mainstem discharge rate for overtopping Slough 9 as16,000 cfs at Gold Creek (for initial breaching) and 19,000 cfs for the river to freely flow through the slough. It is unclear if the change in reported overtopping discharges relative to 1982 is due to changes in stream morphology, or if it reflects a larger dataset with more precise overtopping discharge rates. From monthly water balances performed between July and October of 1984, 80 to 90 percent of precipitation that fell on one tributary watershed formed runoff, while significant streamflow loss occurred for a second tributary stream when flowing over an alluvial fan adjacent to Slough 9. Linear and logarithmic relationships between mainstem and slough discharge were found when the upstream berm of the slough is not overtopped, with r^2 values ranging from 0.82 to 0.84.

9.3. Slough 11 (Gold Creek) Groundwater-Surface Water Interactions

Data collection occurred at Slough 11 in the 1980s, and though not one of the primary focus sloughs, the following study findings were made for Slough 11 with regard to GW/SW interactions:

- Harza-Ebasco (1984a): This report qualitatively notes that little response to precipitation occurred in 1983, and that slough discharge appears closely related to mainstem flow rather than precipitation. Regression equations relating Slough 11 discharge versus mainstem discharge were developed, and it was also concluded that discharge from Slough 11 is mostly related to mainstem discharge (with a r^2 of 0.765). Based on this regression equation, the change in slough discharge relative to mainstem discharge can be estimated for all time periods by multiplying the mainstem discharge by 0.0001. Two seepage meters were installed in Slough 11, with seepage rates from both meters strongly correlated with mainstem discharge (with r^2 values of 0.83 and 0.94).
- Alaska Power Authority (1984): This report compares natural slough upwelling volumes and predicted upwelling volumes following dam construction using a regression curve developed in Harza-Ebasco (1984a). This relationship is presented in Figure 12. This report notes that Slough 11 is hydrologically the simplest slough studied in the 1980s (with little tributary inflow or flow from upstream berm overtopping), and therefore is relatively easy to isolate and study mainstem influences.
- R&M Consultants (1985): This report identifies the mainstem discharge rate for overtopping the Slough 11 berm as 42,000 cfs at Gold Creek. From monthly water balances performed between July and October of 1984, virtually all precipitation that falls in the watershed infiltrates. Linear and logarithmic relationships between mainstem and slough discharge were found when the upstream berm of the slough is not overtopped, with r^2 values ranging from 0.63 to 0.76.

9.4. Slough 21 Groundwater-Surface Water Interactions

Data collection occurred at Slough 21 in the 1980s, and though not one of the primary focus sloughs, the following study findings were made for Slough 21 with regard to GW/SW interactions:

- Harza-Ebasco (1984a): Two seepage meters were installed in Slough 21, with seepage rates either having no correlation to mainstem discharge (in the upper slough) or were negatively correlated (in the lower slough, with increased mainstem flows resulting in decreased seepage rates). These relationships were interpreted to mean that a relatively high proportion of water that discharged at Slough 21 is sourced from adjacent valley uplands or from a deep alluvial flow path originating far upstream.
- Alaska Power Authority (1984): This report further hypothesizes that a large bench of alluvial material (over 0.25 miles wide) upstream of Slough 21 may act as a locally significant aquifer that discharges to the lower slough. Discharge temperatures in the

lower slough were found to be more stable than temperatures in the upper slough, suggesting that the upper slough is likely more affected by mainstem conditions than the lower slough.

10. DAMS IN COLD WEATHER ENVIRONMENTS

Interactions between GW/SW can be significantly impacted by the production of river ice cover and ice jams, both of which can be affected by the management of hydroelectric dams on a river. When a river develops a cover of ice, river stage will characteristically increase while stream flow is diminished because the cross-sectional area is restricted by the ice (frictional and turbulent losses may also occur adjacent to the ice). This increases the surrounding water table or potentiometric surface based on the hydrogeologic properties of the aquifer. In some cases, this can cause GW upwelling at the ground surface outside of the active river channel, or flooding of submerged structures such as basements and sewer systems (National Research Council of Canada 1989; Asvall 1997).

Additionally, the style in which ice cover develops on a river can influence its impact on river flow rates, and therefore GW levels. Quick formation of ice cover in conjunction with steady river discharge will support the production of a homogenous insulating cover of ice that minimizes the restriction of water flowing beneath it, and thus results in a low-likelihood that ice jams will develop. Conversely, inconsistent river discharge and/or significantly fluctuating temperatures can cause developing ice cover to break apart and float downstream, where it risks accumulating in an ice jam or a thicker and more flow-resistant cover of ice (National Research Council of Canada 1989).

11. SUMMARY AND CONCLUSIONS

Hydrogeologic Project reports from the 1980s focused on documenting differences between mainstem and slough temperatures and fluxes in an effort to predict slough flows under post-Project conditions. Water levels in monitoring wells, sloughs, and the mainstem were also documented to better understand slough upwelling flows. Based on detailed studies in Sloughs 9 and 8A, and to a lesser extent in Sloughs 11 and 21, it was concluded that many sloughs exhibit differing and complex hydrologies (with flow regimes affected by tributaries, GW upwelling, berm overtopping, and geologic/geomorphic features) that prevents simple regression relationships between mainstem discharge and slough upwelling from being widely applicable. In general, slough upwelling is affected by mainstem flows, but the relative amount of GW contribution to slough flow can vary in time and space based on mainstem conditions and antecedent precipitation.

Culminating studies from 1984 and 1985 concluded that geologic and hydrologic characteristics of different sloughs should be reviewed and categorized (APA 1984; R&M 1985) to help guide the focus of future studies. Additionally, R&M and WCC (1985) conclude that:

“Detailed projections cannot be made of the slough discharge or temperature variations which might result from changes in mainstem conditions as a result of project operation. Because of the substantial differences among the sloughs in their hydraulic and thermal behavior, it would be necessary to construct mathematical models of each individual slough in order to make detailed predictions of the effects on the sloughs of changes in mainstem conditions."

Figure 13 is reproduced from R&M and WCC (1985) and plots the hydrologic responses of different sloughs and the mainstem to a storm event. As evident in the figure, different sloughs have different responses, and because of these differences, substantial hydrogeologic data (including aquifer extent and thickness, horizontal and vertical hydraulic conductivities, storage coefficients, horizontal and vertical hydraulic gradients) will be needed to accurately model each slough. Similarly, APA (1984) concluded that extensive drilling and aquifer testing would be needed to completely evaluate possible sources of GW upwelling in the sloughs, and that it is possible that even with such data such analyses may not succeed.

A hydrid approach would include reviewing differentiating characteristics of sloughs (such as the presence of tributaries, upland soil/geology type, apparent influence from mainstem flows, influence from overtopped-berm flows, etc.) and their hydrologic responses to see if sloughs with similar characteristics show similar responses. If this is the case, representative sloughs could then be focused on and potentially modeled, with simulated results extrapolated to other sloughs that are expected to have similar responses. Much of the water level and temperature data necessary for initial comparisons have already been collected at multiple sloughs.

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14. TABLES

Table 1. Summary of hydrogeologic parameters identified from the 1980s groundwater studies and other relevant materials for the Susitna River watershed, Alaska.

Source	Location or Study Area	Alluvial Aquifer Sediment Thickness (ft)	Alluvial Aquifer Saturated Thickness (ft)	Alluvial Aquifer Extent (ft)	Alluvial Aquifer Kh (ft/d)	Alluvial Aquifer Kv (ft/d)	T (ft2/d)	Storage Coeff.	Horizontal Hydraulic Gradient
Acres American (1980)	Devil Canyon	**35**							
Acres American (1980)	Vee (~ PRM 224)	**125**							
Acres American (1980)	Watana	**50 - 80**							
Acres (1982)	Watana	**40 - 80**							
R&M Consultants (1982)	Slough 8A	**> 9.5**			*226 - 1000; 328 - 3280 assumed for calculations*			*0.2*	**0.0022 - 0.003**
R&M Consultants (1982)	Slough 9	**> 11**							
R&M Consultants (1982)	Slough 9B	**> 43**	**> 35**					*0.2*	**0.0033**
Acres American (1983)	Slough 9		*100*		*170 - 1000; 200 assumed for calculations*		*9,000*	*0.18*	
Harza-Ebasco (1983)	Watana	**mean 80, locally up to 140**			**4.3 – 340, low bias since only fine grained sediments tested**				
Harza-Ebasco (1984)	Slough 8A to 11, Middle Susitna River		*100*	**3000^**	67		*6,700*	*0.2 (unconf); 0.0002 (conf)*	*0.003*
Harza-Ebasco (1984)	Talkeetna Fire Hall	**> 100**	**> 70**		**84**		**1858 - 5900***		
Harza-Ebasco (1984)	Talkeetna Area Wells				**22 - 133 (mean 57)**		*334 - 1070*		
Harza-Ebasco (1984)	Middle Susitna River Valley Walls		*500*		*0.014*		*7.1*		*0.3*
R&M Consultants (1985)	Slough 9				**0.15 - 31**		**0.2 - 92**		
R&M Consultants & Woodward-Clyde (1985)	Gold Creek Railway Bridge	**100**							
Penn Jersey Drilling (2007)	Curry	**> 120**	**> 70**		**123**		**7600**		
USGS (2013)	Lower Susitna Basin	*250 - 400*			*16.9 - 19.2*	*1 (riverbed sediments)*			*0.004 - 0.006*

Notes:

1 Kh = horizontal hydraulic conductivity; Kv = vertical hydraulic conductivity; T = transmissivity;

2 Bold values are measured values, italicized values are either assumed, estimated, or calibrated values.

3 Vertical hydraulic gradient data were presented, and therefore are not tabulated.

4 Interpretation of valley-fill sediment extent was based on aerial photos between Slough 11 and 8A.

5 See text Section 5.2 for a discussion of transmissivity interpretations.

15. FIGURES

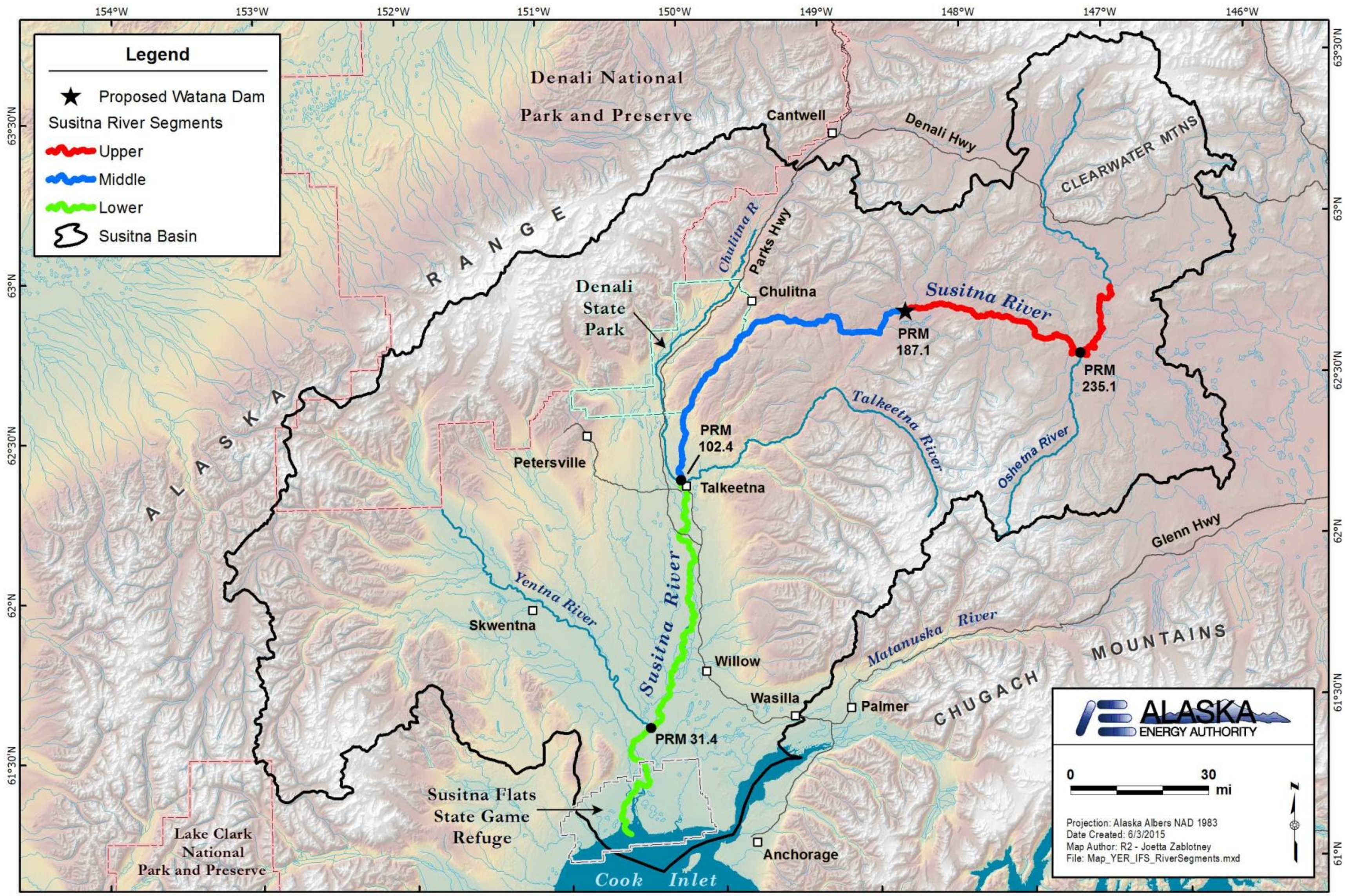


Figure 1. Susitna Watershed basin boundaries, showing the Project designation of Upper, Middle, and Lower Susitna River segments.

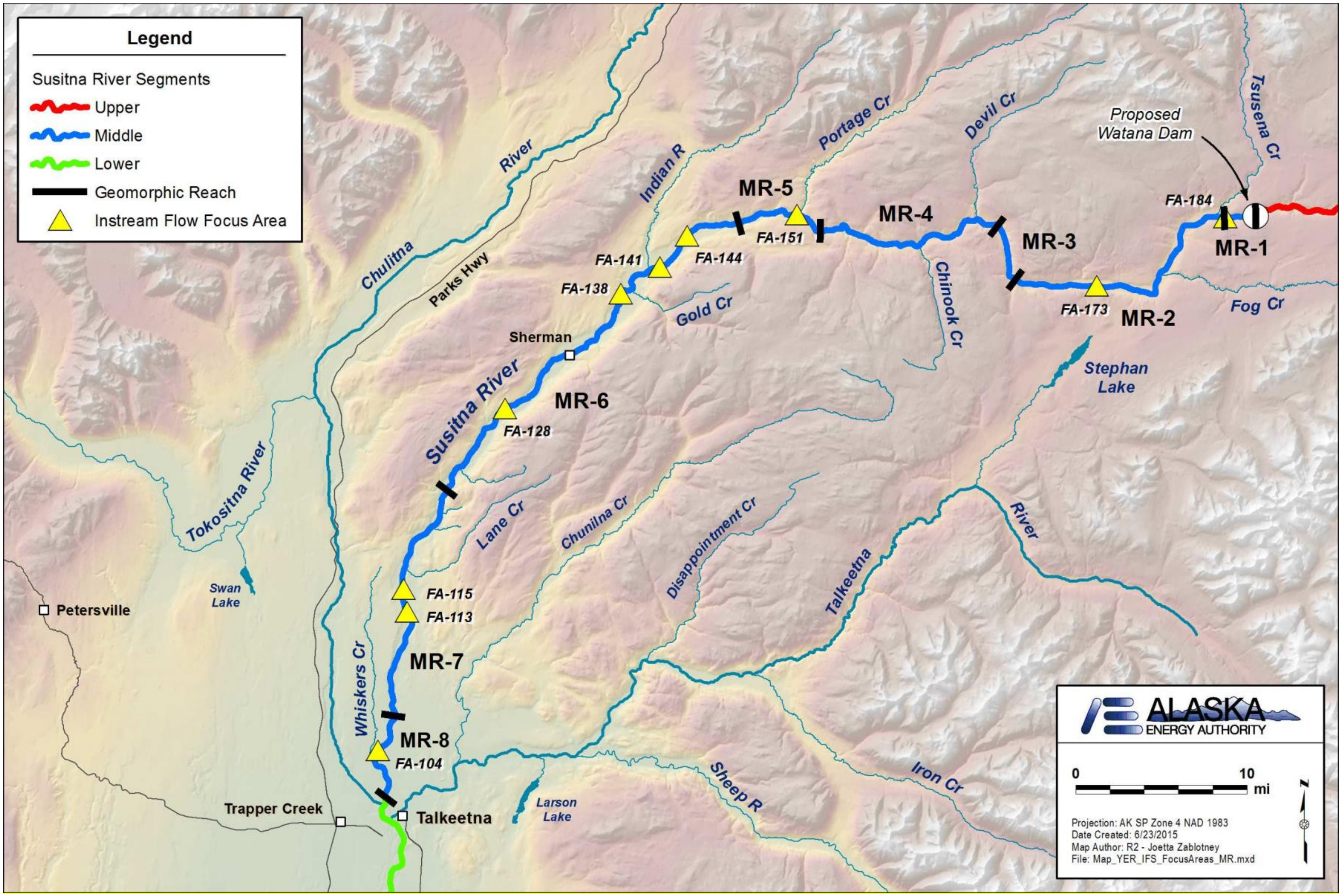


Figure 2. Susitna Watershed Middle Susitna River Segment, with geomorphic reaches and Focus Areas indicated.

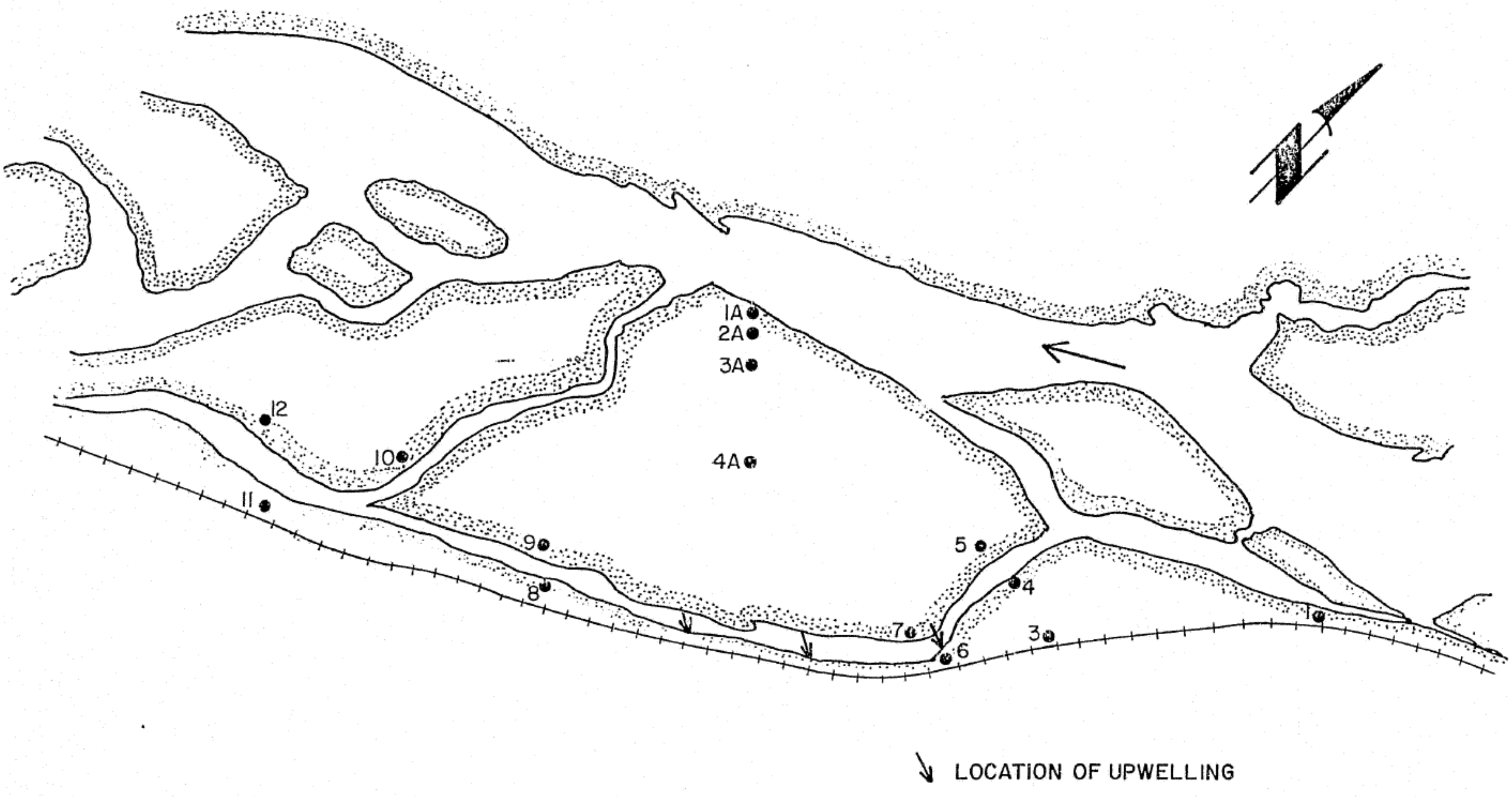


Figure 3. Observed locations of groundwater upwelling in Slough 8A, in the Middle Susitna River Segment of the Susitna River, from R&M Consultants, (1982).

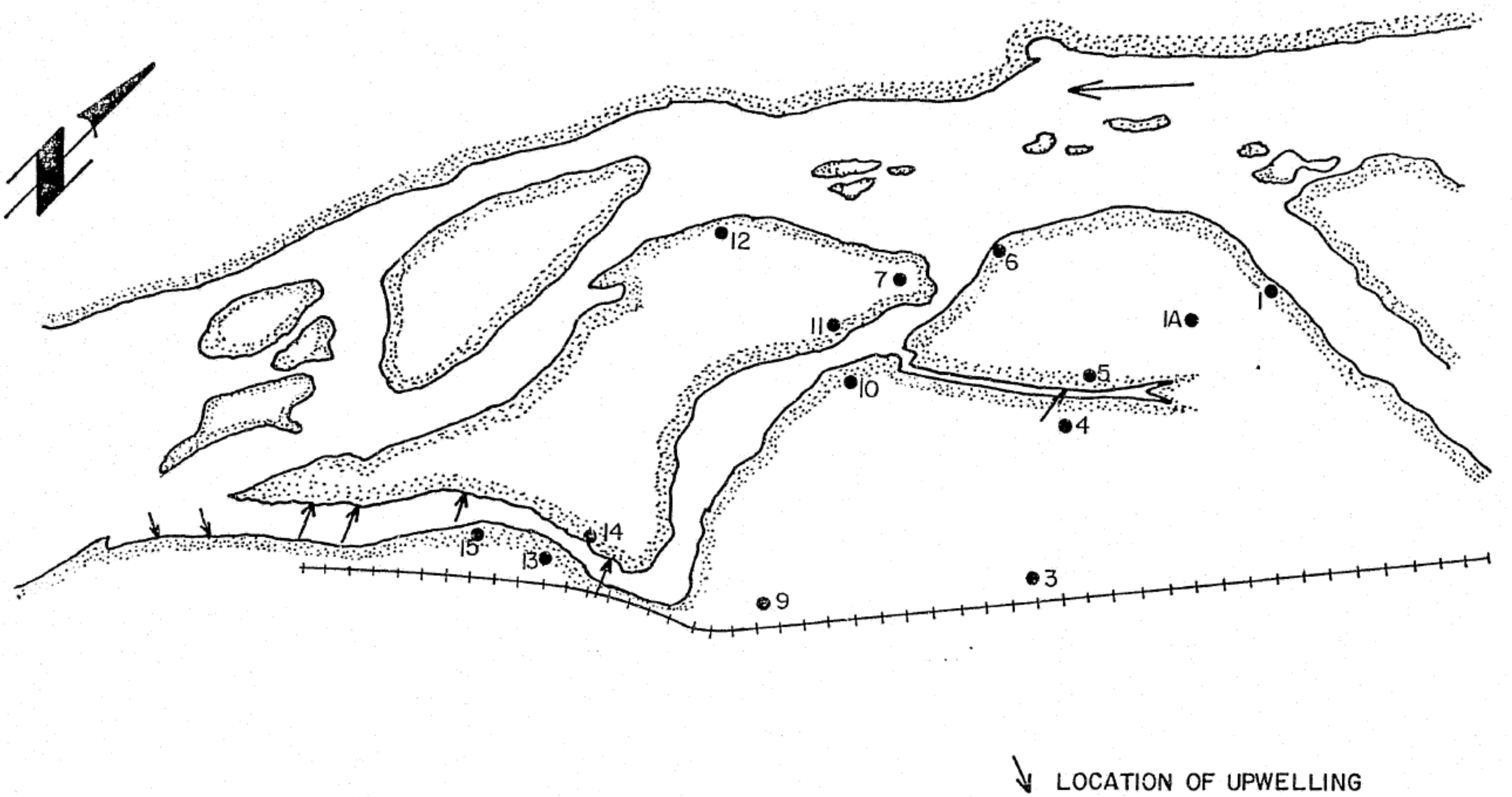


Figure 4. Observed locations of groundwater upwelling in Slough 9 in the Middle Susitna River Segment of the Susitna River, from R&M Consultants, (1982). Slough 9B is located between wells 4 and 5.

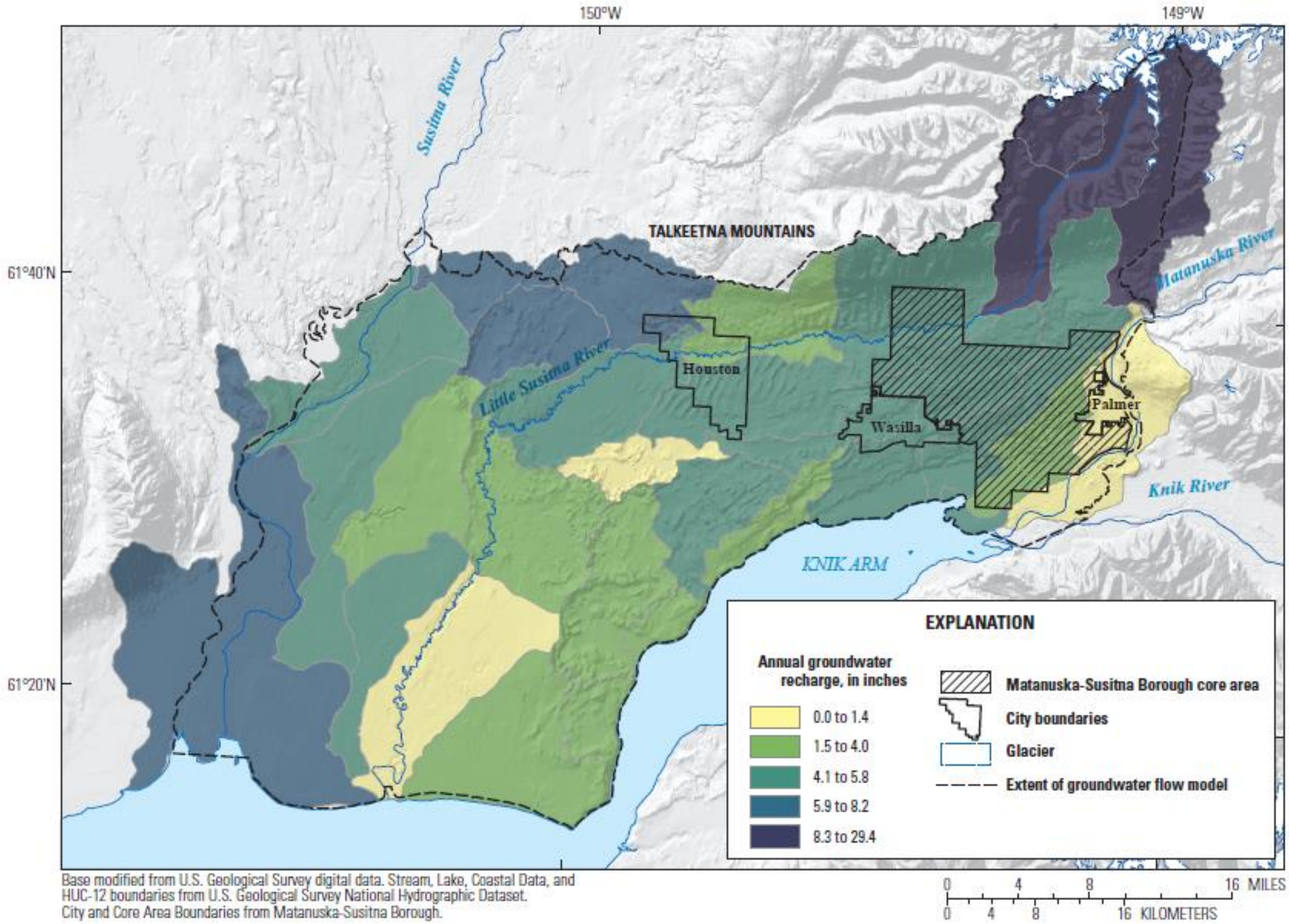


Figure 5. Groundwater recharge for part of the Lower Susitna River Segment, from USGS (2013).

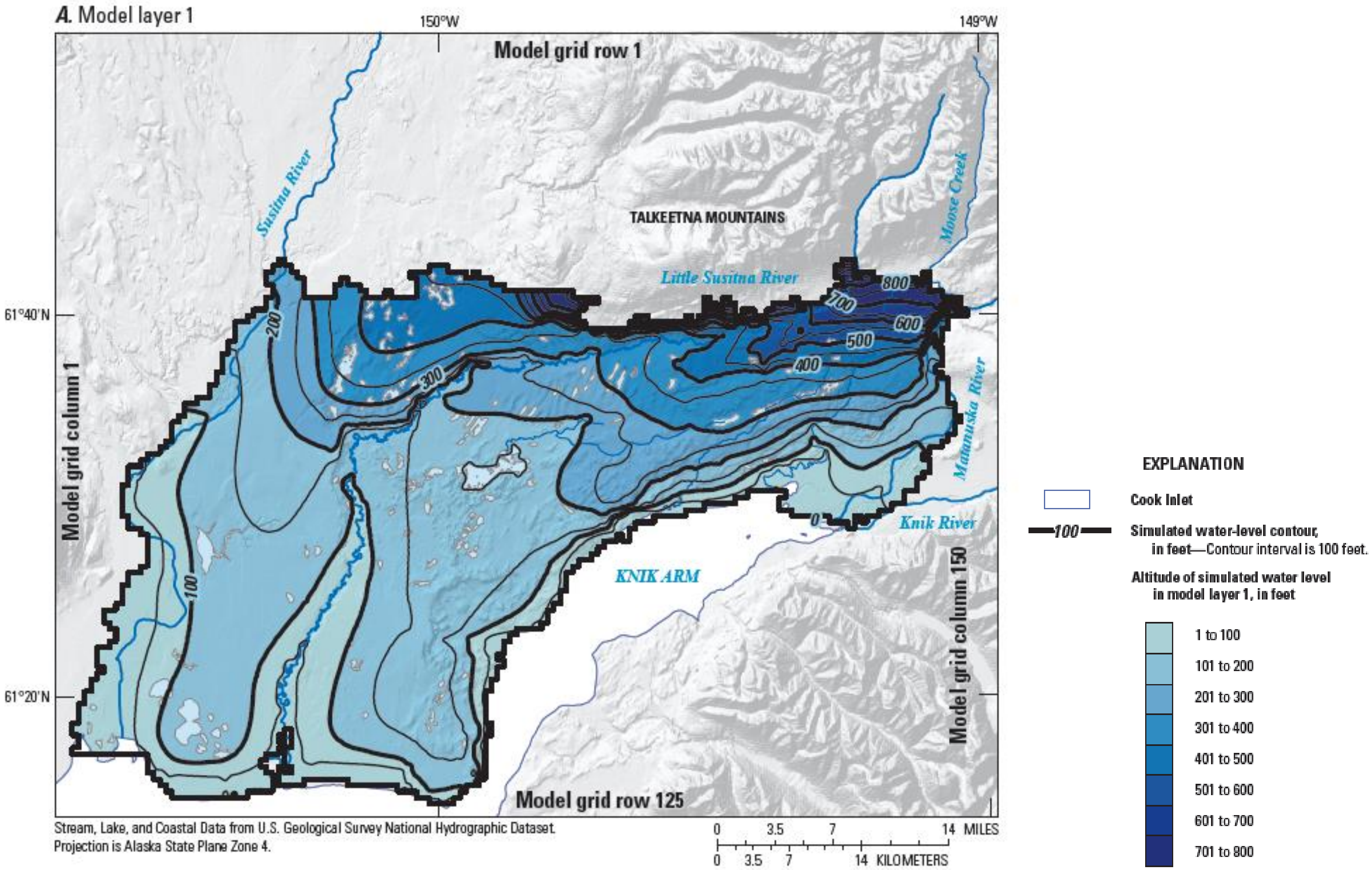


Figure 6. Simulated water levels for shallow sediments in the Matanuska-Susitna Valley, Alaska, from USGS (2013).

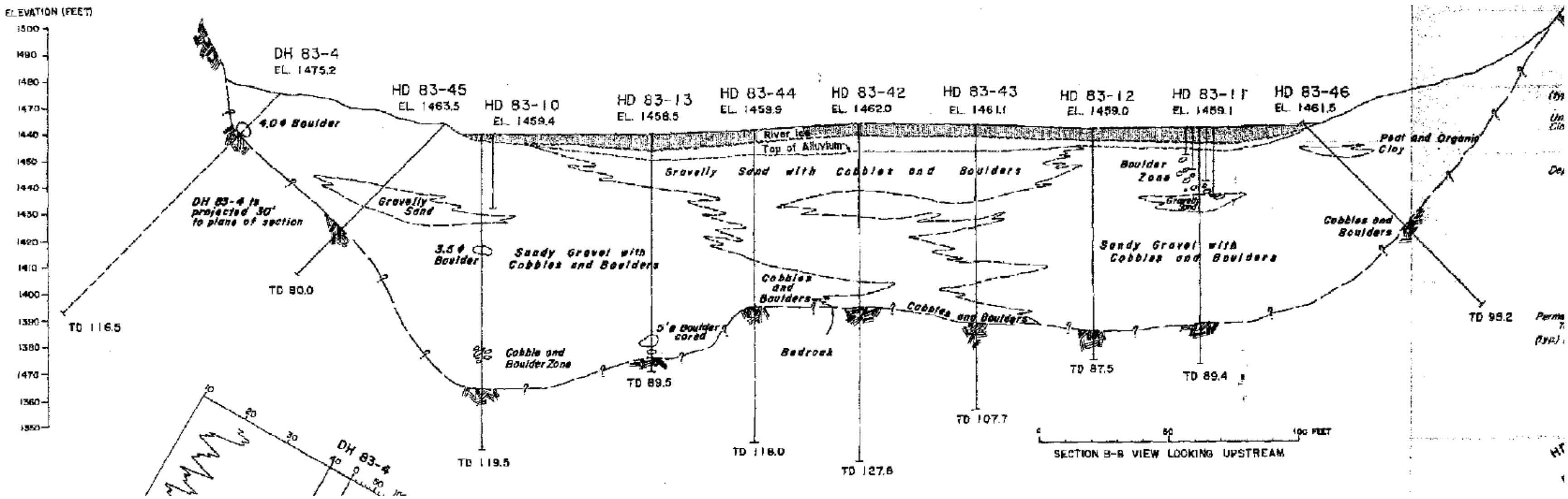
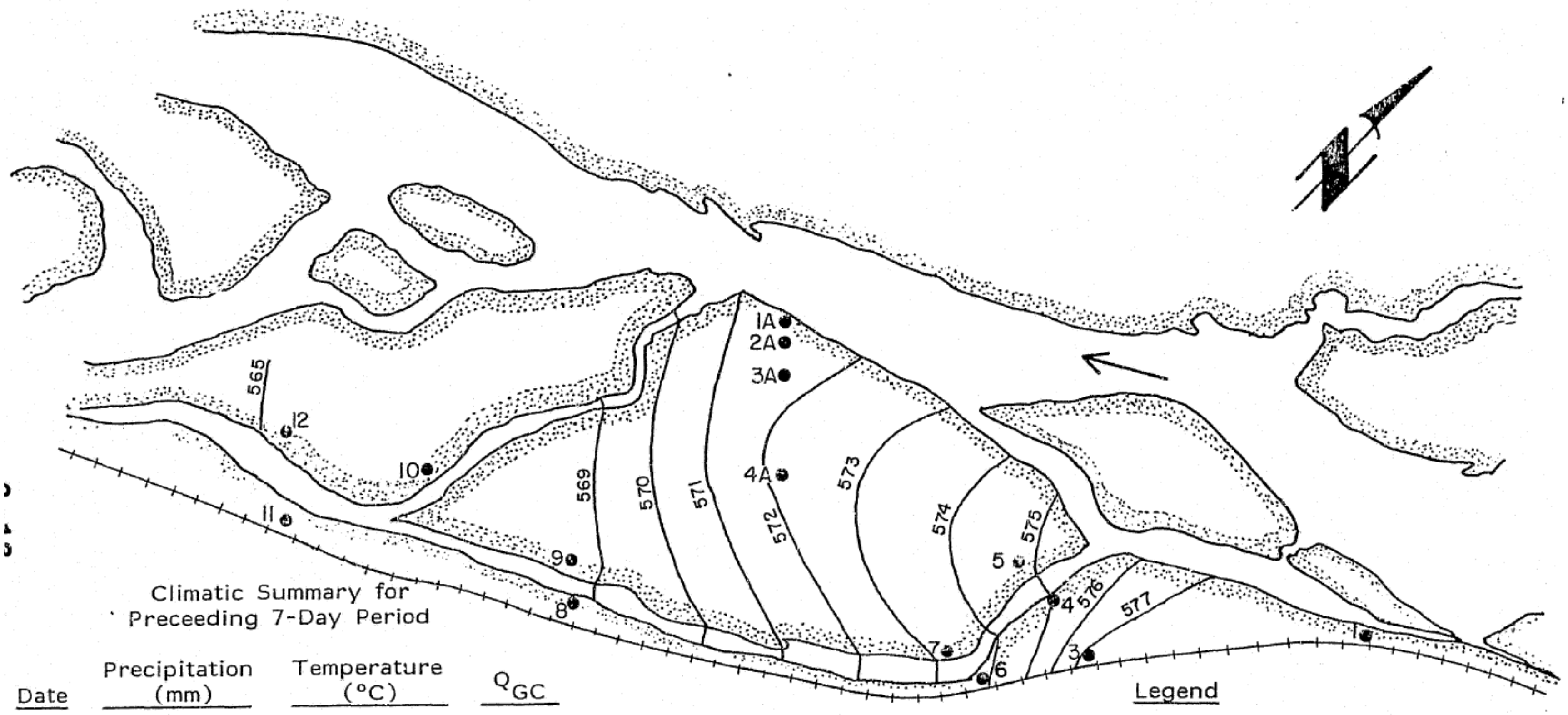


Figure 7. Geologic Cross-section of the Susitna River Channel at the Watana Dam Site, from Harza-Ebasco (1983).



Climatic Summary for Preceeding 7-Day Period

Date	Precipitation (mm)	Temperature (°C)	Q_{GC}
8-28	3.2	9.8	12,400
8-29	13.2	9.8	12,200
8-30	27.2	8.5	13,100
8-31	7.8	9.8	16,000
9-1	9.4	10.3	17,900
9-2	11.6	9.2	16,000
9-3	7.8	8.3	14,600

Legend

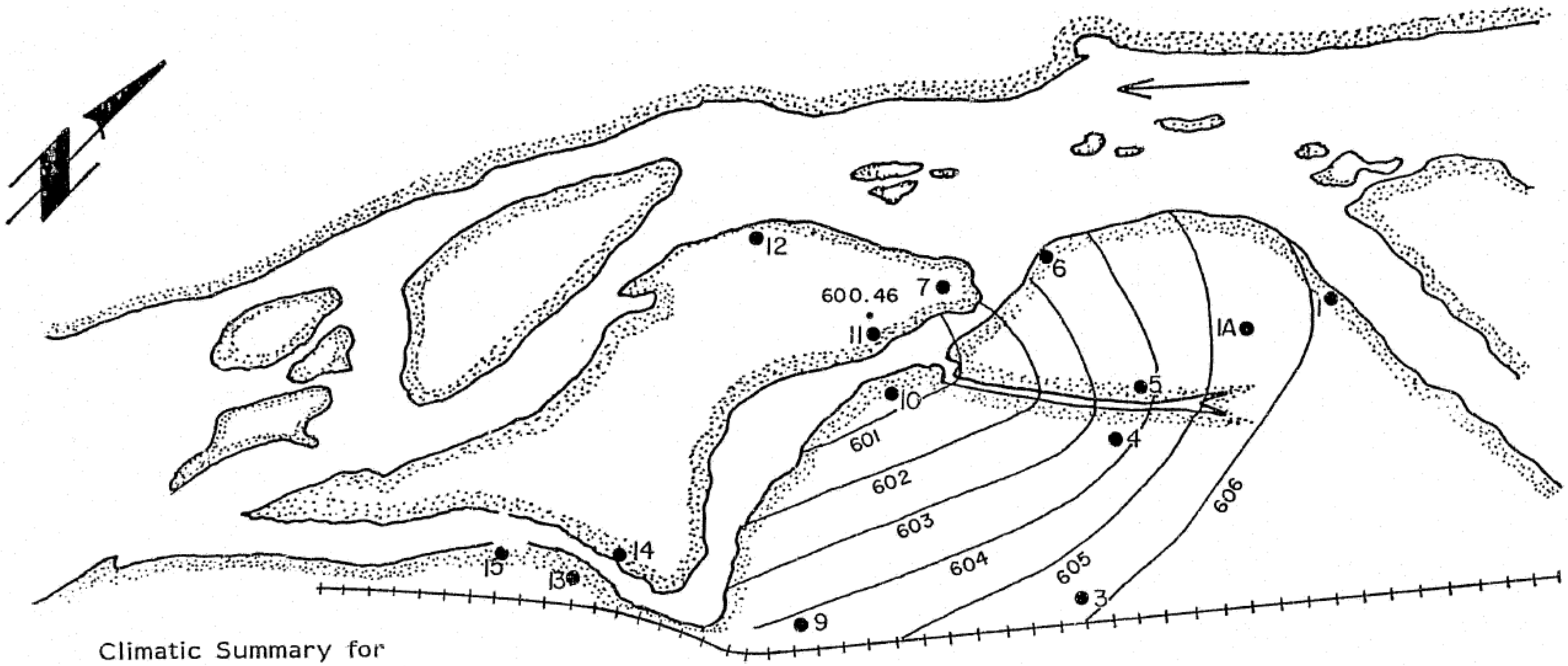
o observation well

"600" groundwater elevation

Date: 9-3-82

Q_{GC}: 14,600

Figure 8. Example groundwater contour map for Slough 8A, from R&M Consultants, (1982).



Climatic Summary for
Preceeding 7-Day Period

Date	Precipitation (mm)	Temperature (°C)	Q_{GC}
8-31	7.8	9.8	16,000
9-1	9.4	10.3	17,900
9-2	11.6	9.2	16,000
9-3	7.8	8.3	14,600
9-4	0.2	7.8	14,400
9-5	1.0	9.9	13,600
9-6	0.0	10.3	12,200

Legend

●	observation well
"600"	groundwater elevation
Date:	9-6-82
Q_{GC}:	12,200

Figure 9. Example groundwater contour map for Slough 9, from R&M Consultants, (1982).

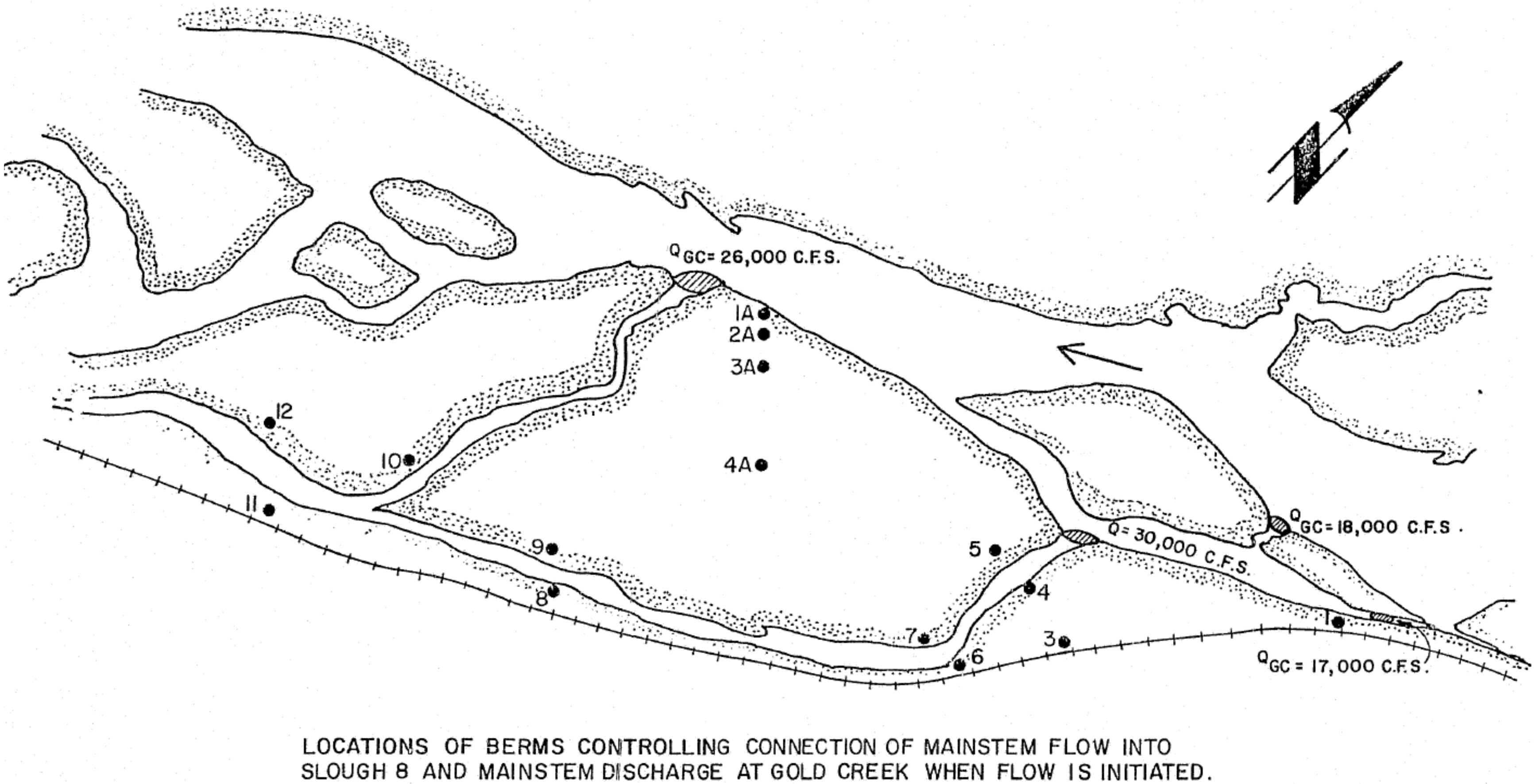


Figure 10. Slough 8A controlling berm locations, from R&M Consultants, (1982).

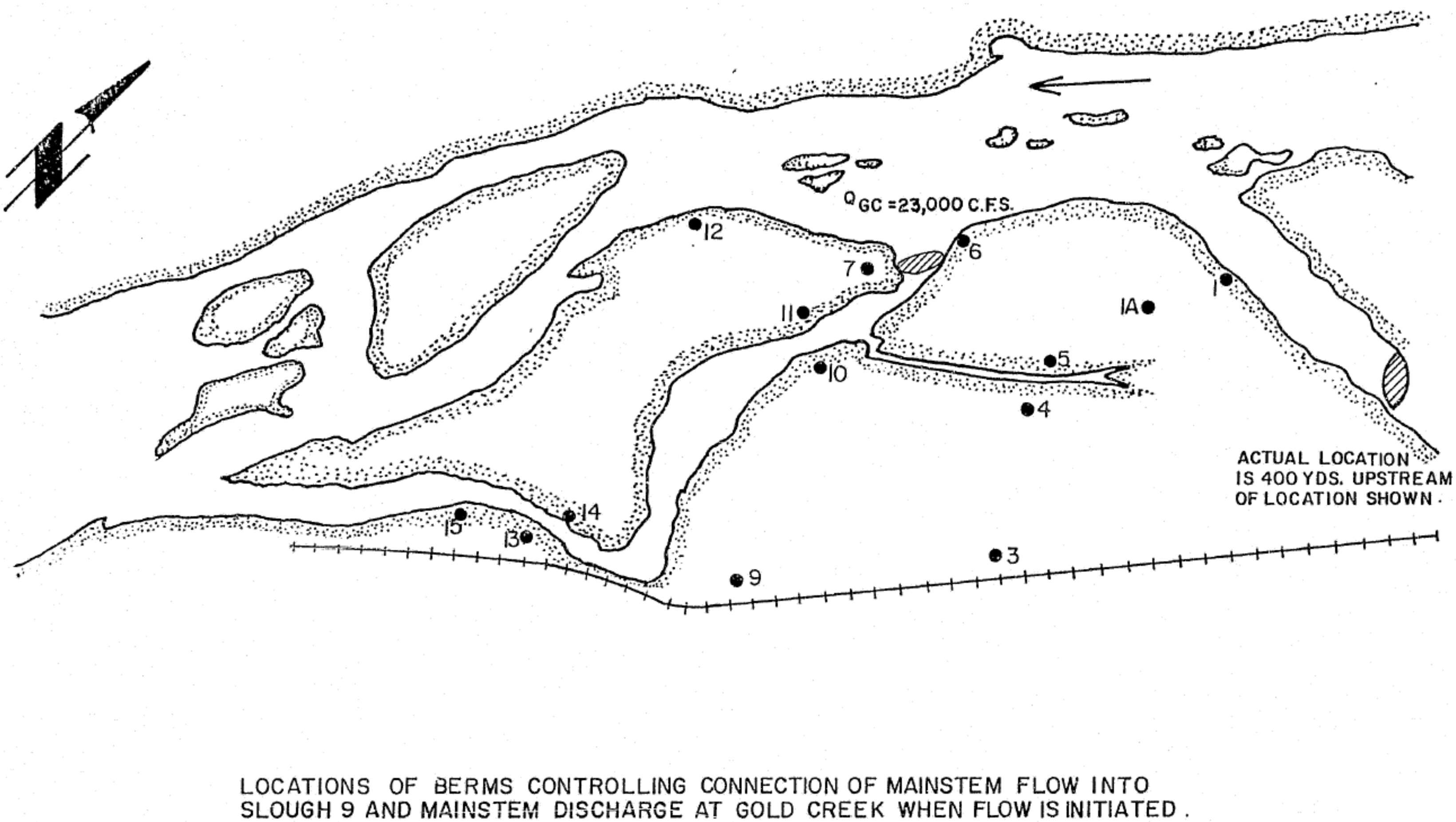


Figure 11. Slough 9 controlling berm location, from R&M Consultants, (1982).

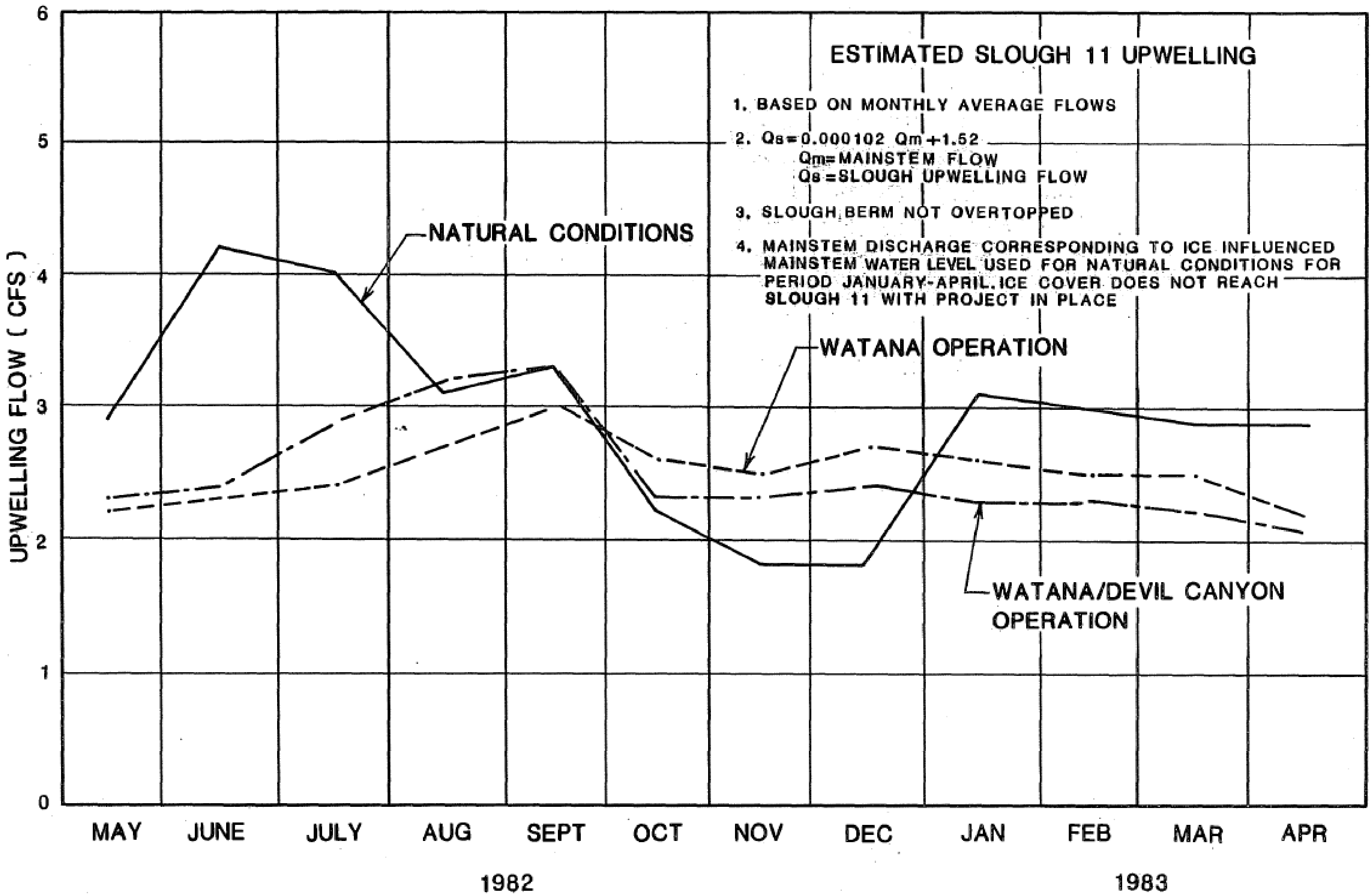


Figure 12. Estimated Slough 11 Upwelling Under Natural and With-Project Conditions, from APA (1984).

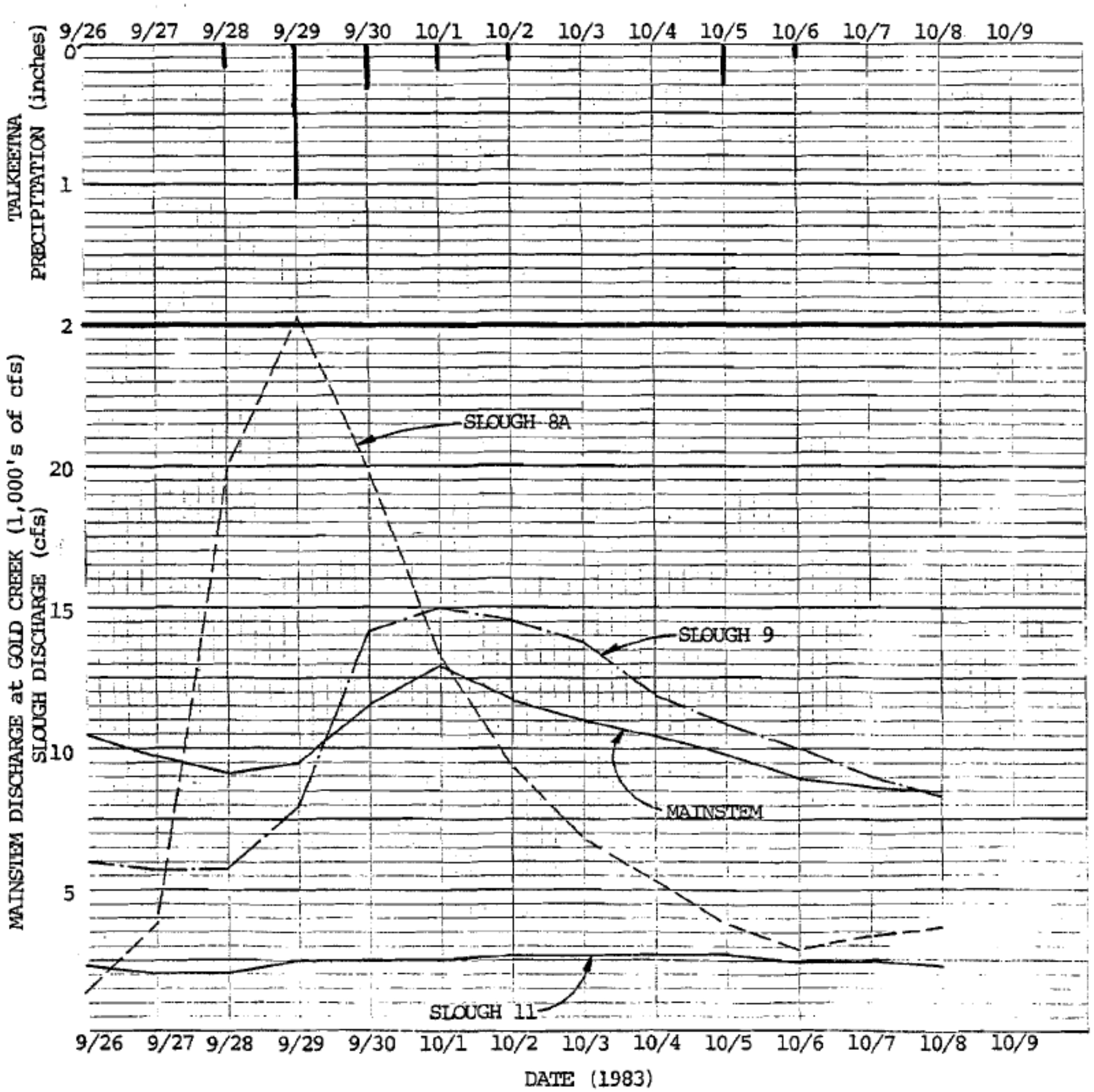


Figure 13. Response of Susitna River and Sloughs 8A, 9, and 11 to a September 1983 Storm, from R&M Consultants and Woodward-Clyde Consultants (1985).