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FEDERAL ENERGY REGULATORY COMMISSION
SUSITNA HYDROELECTRIC PROJECT
PROJECT NO. 7114

ALASKA POWER AUTHORITY COMMENTS ON THE FEDERAL ENERGY REGULATORY COMMISSION DRAFT ENVIRONMENTAL IMPACT STATEMENT OF MAY 1984

Volume 9

Appendix VII - Slough Geohydrology Studies

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August 1984

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1.0 SUMMARY

The purpose of the present study was to investigate the relationships between flow and temperatures of the mainstem Susitna River and quantities and temperatures of upwelling groundwater in side sloughs tributary to the Susitna River in the reach between Devil Canyon and Talkeetna. Four sloughs representing important salmon habitat areas were examined in some detail. These sloughs are designated as 8A, 9, 11 and 21.

Information on groundwater flow to the sloughs was requested by the Federal Energy Regulatory Commission (FERC) in their April 12, 1983 Request for Supplemental Information, Schedule B, Exhibit E, No. 2.34. The Alaska Power Authority's response was filed with the FERC on July 11, 1983. This report presents the results of studies which were ongoing at the time of that response.

A considerable amount of data has been collected over the last two years in these sloughs by the Alaska Department of Fish and Game and R & M Consultants. The present study was based on a review of these data, visits to the site and conversations with project personnel and others, including representatives of the U.S. Geological Survey, the Alaska Department of Geological and Geophysical Surveys, and the U.S. Fish and Wildlife Service.

The following conclusions have been reached:

1. It is not possible using the existing data to make a complete evaluation of the possible sources of groundwater upwelling to the sloughs. Such an evaluation could require extensive drilling and aquifer testing. These activities would be very expensive and it is possible that the results might not provide the data required. Thus it is not presently considered economically justifiable to perform such activities.

2. It is possible, applying our best professional judgment to the available data, to isolate the apparent groundwater upwelling component of slough discharge at Sloughs 8A, 9 and 11. Using elementary statistics, correlations between mainstem flow and the upwelling flows can be estimated. Such relationships are shown on Figures 1, 2, and 3 for Sloughs 8A, 9 and 11, respectively. Variations in the inferred upwelling component are between 0.0001 and 0.00035 of corresponding variations in mainstem discharge measured at Gold Creek. These statistical inferences are felt to be strongest at Slough 11, less strong at Slough 9 and relatively weak at Slough 8A. Nonetheless, we believe these relationships are suitable for making preliminary analyses regarding project-related changes in the groundwater upwelling component of slough discharge. Further studies to refine these relationships are included in our FY85 Scope of Work.

The relationship at Slough 11 may be indicative of the behavior of the groundwater upwelling component of slough flow at other sloughs in the study area. Slough 11 is the least complicated of the study sloughs, with little flow resulting from either local runoff or upstream berm overtopping. Consequently, the upwelling component of slough discharge at Slough 11 is relatively easy to isolate and to relate to mainstem conditions. The general relationship between slough discharge and mainstem discharge is illustrated by the regression line shown on Figure 3. With-project river discharge will often be lower than the mainstem discharge values used to develop this relationship and caution must be used in extrapolating the relationship for very low flows. Based on this linear regression relationship, Figure 4 shows the expected groundwater upwelling on a monthly average basis at Slough 11 for Watana operation and Watana/Devil Canyon operation for the period May 1982 to April 1983 with a comparison to naturally-occurring upwelling estimated in a similar manner. For the winter months of January through April, a mainstem discharge corresponding to the ice-influenced mainstem stage, rather than the actual mainstem discharge, was used in applying the regression equation to develop Figure 4. Additional studies will be conducted during FY85 to confirm and clarify relationships between upwelling rates and mainstem stage, rather than discharge.

Based on these apparent relationships, groundwater upwelling would continue throughout the year with project operation. It must be remembered, however, that for most of the sloughs in the river reach of interest, groundwater upwelling is only one factor affecting the fisheries habitat of the slough, particularly during the open-water season. Tributary runoff and overtopping of upstream berms can be important influences on the slough habitats.

3. The temperature of the groundwater discharge to the sloughs appears to remain relatively constant at a value approximately equal to the mean annual (time-weighted) river temperature. Changes in mean annual river temperature resulting from project operation will probably be reflected in the temperature of the groundwater upwelling component. Based on currently available temperature simulations, the mean annual temperature of the Susitna River at Slough 9 would be approximately 3.9° C, for natural conditions, in the period May 1982 - April 1983. With Watana in operation, the mean annual temperature would be 4.3° C for the same period. With Devil Canyon in operation, the mean annual temperature would be 4.1° C. This suggests that the temperature of groundwater upwelling would increase slightly with project implementation. However, these differences in estimated mean annual temperatures are small enough that they may not represent significant changes.

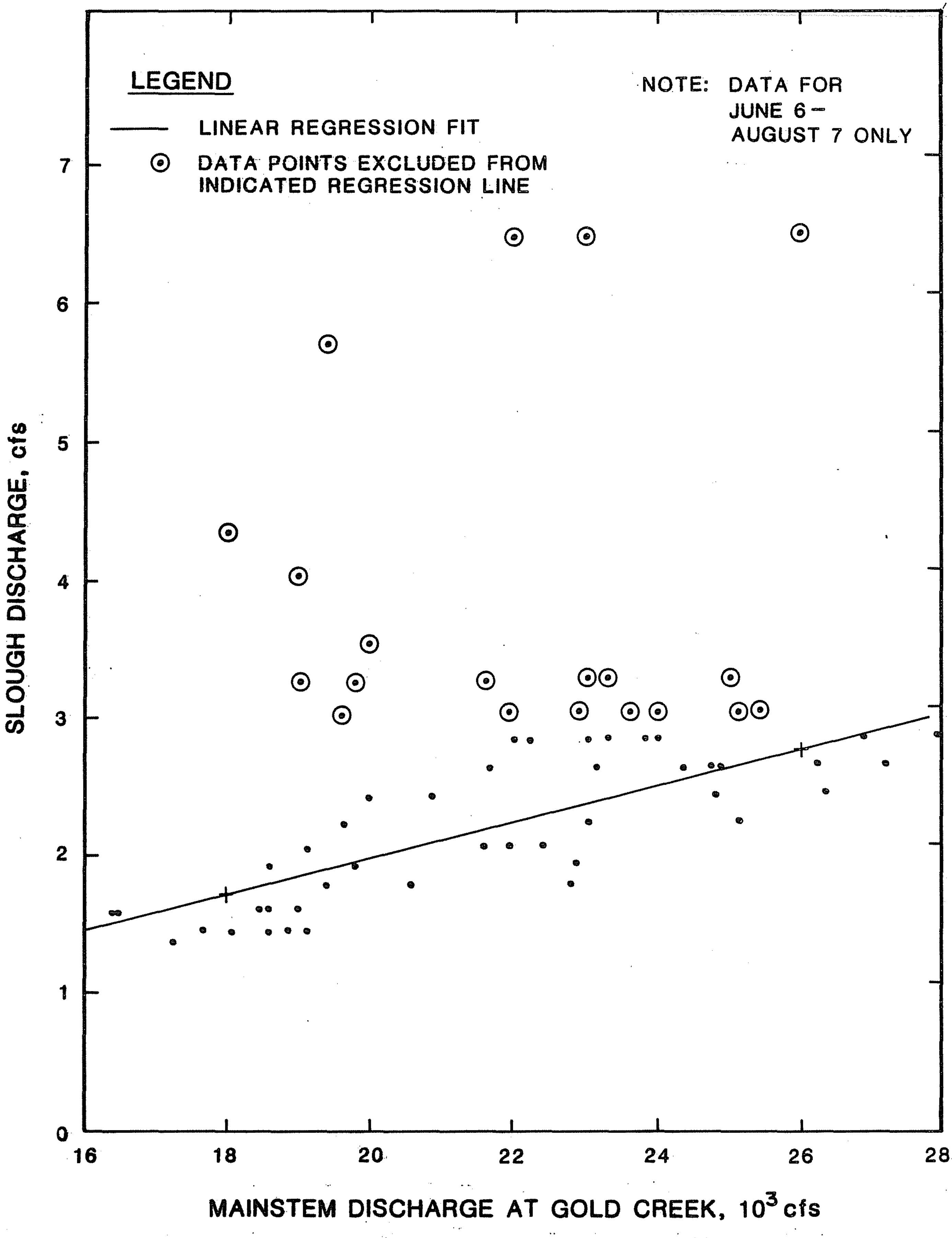
Project implementation is expected to result in the following general changes in groundwater upwelling:

1. During the period of May to September, with-project discharges will be less than natural, resulting in a reduction in groundwater upwelling in the sloughs.

2. During the period October to April, with-project discharges exceed natural discharges. An ice cover will form on the river during this period. At a given slough, the mainstem water surface elevation will depend on ice processes and it will be possible to estimate how groundwater upwelling during project operation would compare to natural conditions when results of ice modeling are available.

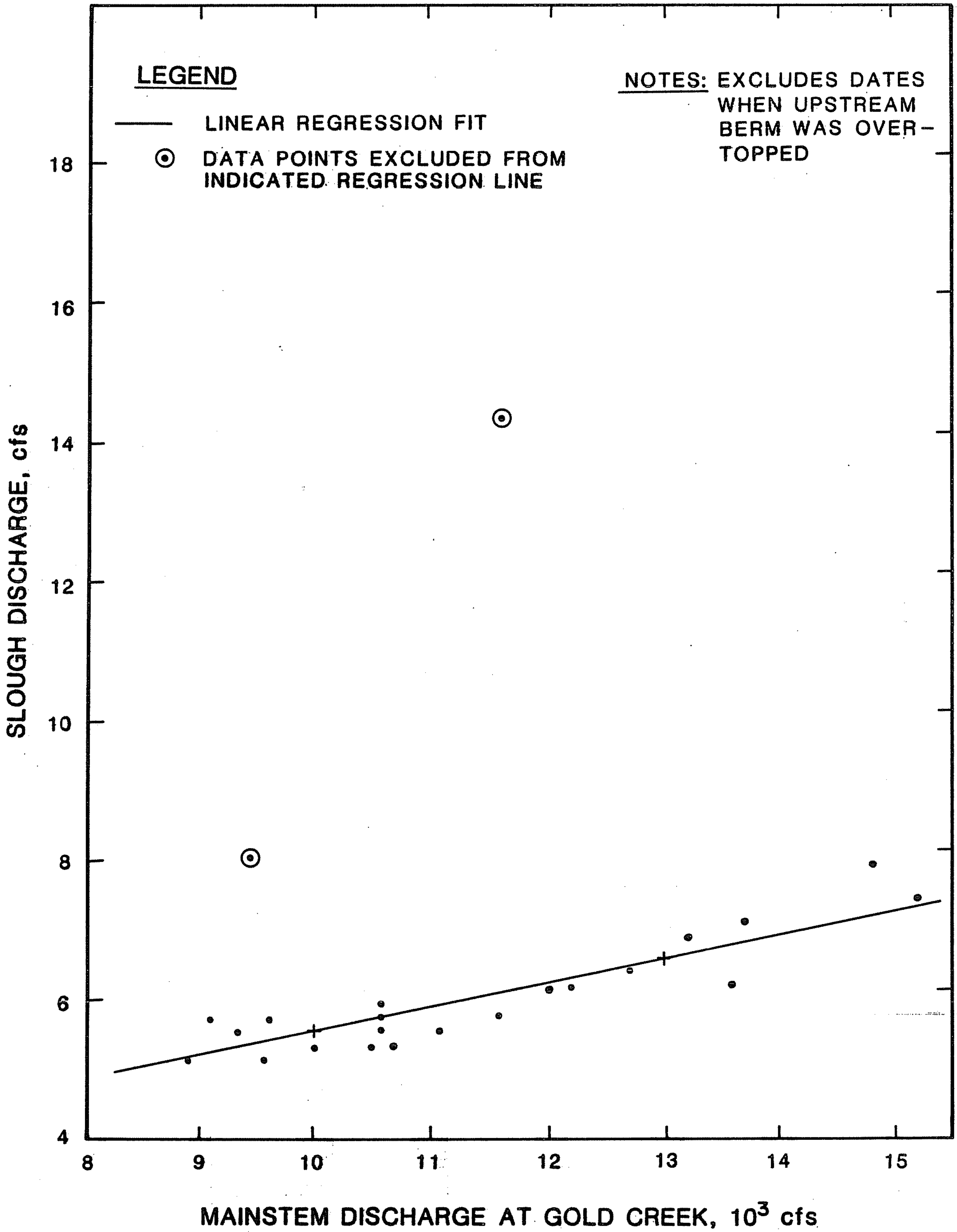
3. It may be possible to more accurately estimate the changes in temperature of groundwater upwelling when results of instream ice and instream temperature modeling are available.

4. Project implementation is expected to reduce fluctuations in mainstem Susitna River discharge and temperature. This is expected to result in more stable groundwater upwelling flows and temperatures.



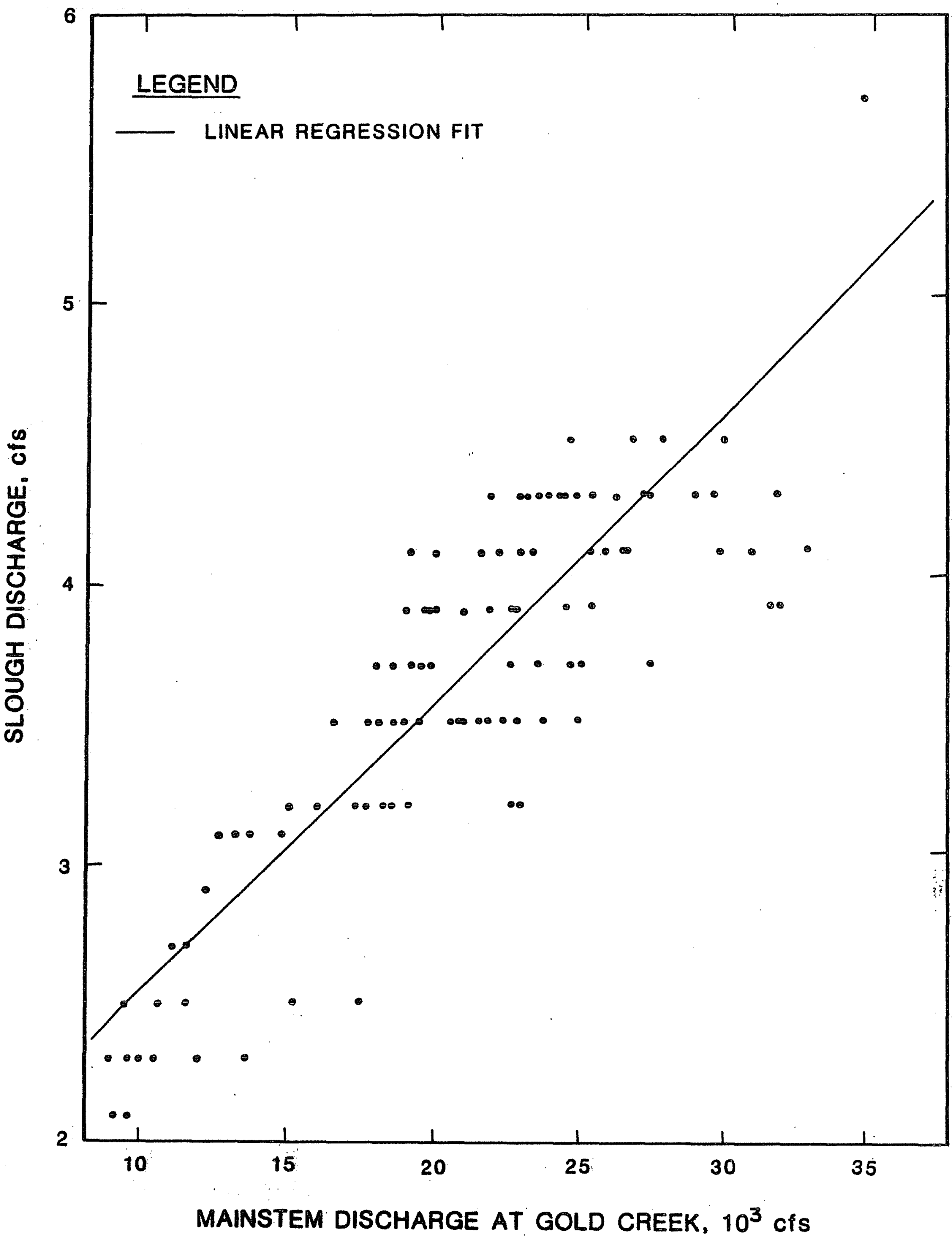
SLOUGH 8A DISCHARGE VS. MAINSTEM DISCHARGE AT GOLD CREEK, SUMMER 1983

HARZA-EBASCO
SUSITNA JOINT VENTURE



SLOUGH 9 DISCHARGE VS. MAINSTEM DISCHARGE AT GOLD CREEK, SUMMER 1983

HARZA-EBASCO
SUSITNA JOINT VENTURE



SLOUGH 11 DISCHARGE VS. MAINSTEM DISCHARGE AT GOLD CREEK, SUMMER 1983

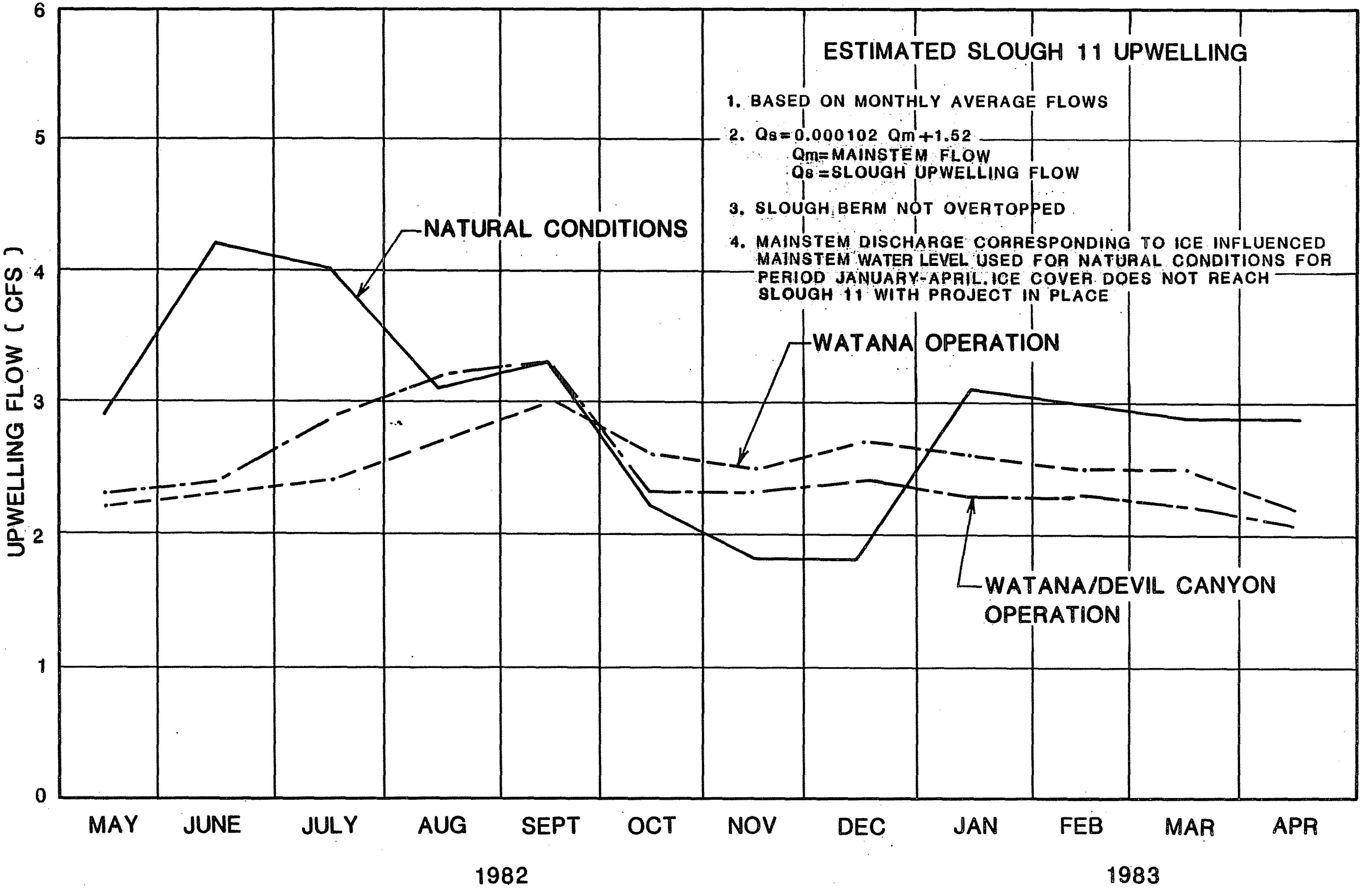


FIGURE 4

HARZA-EBASCO
SUSITNA JOINT VENTURE

2.0 INTRODUCTION

This report provides results of a study begun by the Harza-Ebasco Joint Venture in September 1983 to evaluate hydrologic conditions affecting side sloughs of the Susitna River between Devil Canyon and Talkeetna, downstream of the proposed Susitna Hydroelectric Project. Because of the importance of these sloughs as salmon spawning and rearing areas, and the possibility that groundwater discharge to the sloughs is derived from the mainstem, the current study involves evaluation of existing data to determine whether hydraulic and thermal relationships might exist between mainstem flows and slough flows. The basic objective of this study is to predict possible variations in the amount and temperature of groundwater discharge to the sloughs as a result of variations in mainstem flows and temperatures induced by project operations.

The current study is based largely on data collected during 1982 and 1983 by R&M Consultants as a subcontractor to the Joint Venture, and by the ADF&G Su Hydro Aquatic Studies Group. Data were collected primarily from the vicinity of four sloughs, 8A, 9, 11, and 21, whose locations are shown on Exhibit 1. Those data have been used in a variety of statistical and other mathematical analyses in an attempt to identify significant interrelationships between mainstem and slough discharge and temperature.

3.0 METHODOLOGY

3.1 DATA COMPILATION AND REVIEW

A variety of surface water, groundwater, and water quality data have been compiled from sources such as ADF&G, U.S. Geological Survey, and published and unpublished reports prepared for this and other projects. The types of data which were available include the following:

- Aquifer test data, specific capacity data, and well logs from shallow wells in the Talkeetna area.
- Groundwater level data - occasional water level measurements during 1982 from sixteen wells and shallow standpipes near slough 8 and sixteen wells and shallow standpipes near slough 9; continuous datapod water level records during 1983 from three wells near slough 9.
- Aerial photographs.
- Mainstem discharge data - daily records from the USGS gaging station at Gold Creek for 1982 and 1983.
- Mainstem water surface elevation data - obtained from periodic staff gage readings during 1982 and 1983 at 33 stations in the vicinity of Sloughs 8A, 9, 11, and 21; water surface profiles predicted by hydraulic modeling.
- Slough discharge data - daily records during the summer of 1982 from gaging stations in sloughs 9 and 11, and daily records during the summer of 1983 from gaging stations in sloughs 8A, 9, and 11.

- Seepage meter data - measurements of seepage rates into sloughs made at various mainstem water surface elevations during 1983 at nine seepage meters in sloughs 8A, 9, 11, and 21.

- Summer 1982 and 1983 weather data from the Sherman weather station.

- Groundwater temperature data - occasional temperature measurements during 1982 from fifteen wells near slough 8A and from fourteen wells near slough 9; continuous datapod records during late 1982 through 1983 from three wells near slough 9.

- Occasional 1982 temperature measurements at various mainstem (two locations, near each of sloughs 8A and 9) and slough (sloughs 6A, 8A, 9, 9A, 9B, 10, 11, 20, 21, and 22) locations.

- Intermittent mainstem temperature data for the summer of 1982 through the summer of 1983 (seventeen locations between Talkeetna and Devil Canyon); intermittent slough temperature data for the winter and autumn of 1982 through the summer of 1983 (sloughs 8A, 9, 11, 16, 19, and 21).

- Miscellaneous water quality data from several mainstem and slough locations.

Approximate locations of the sources of data discussed in this report are shown on Exhibits 2 through 9. Exhibit 2 shows locations of stage recorders and seepage meters in sloughs 8A, 9, 11, and 21. Exhibit 3 shows locations of surface water elevation measuring points in and near sloughs 8A, 9, 11, and 21. Exhibits 4, 5, and 6 show locations of surface water temperature measuring points in, respectively, the summer of 1982, winter of 1982-83, and summer of 1983. Exhibits 7 and 8 show the locations of observation wells at sloughs 8A and 9, respectively.

Exhibit 9 shows the locations of water supply wells in the Talkeetna area. All of the data measuring points shown on Exhibits 2 through 9 are approximately located. In most cases, locations were determined from coordinates or verbal descriptions, rather than maps, and thus could not be precisely plotted. Nonetheless, it is believed that the locations are sufficiently accurate to support the applications of the recorded data made in this study.

3.2 SITE VISITS

A site reconnaissance trip was conducted on September 21 and 22, 1983. The visits were made during a period of relatively low mainstem discharge (approximately 10,000 cfs), so the presence of groundwater inflow to the sloughs was more apparent than it would have been had the sloughs been conveying turbid water due to their upstream berms being overtopped by higher mainstem flows.

During the afternoon of September 21, helicopter flyovers of several sloughs between Talkeetna and slough 11 were made, with stops at sloughs 8A, 9, and 11 for more direct observations. In these sloughs, several observations were made of seepage and upwelling. In addition, instrumentation including staff gages, stage recorders, and seepage meters was observed on the ground, and monitoring wells at slough 9 were observed from the air. Lower reaches of slough 11 were toured on foot, and the servicing of instrumentation at well 9-1A was observed. Several sloughs upstream of slough 11, and Devil Canyon, were observed from the air in flying to Watana Camp at the end of the day.

On September 22, the lower reaches of slough 9 were toured on foot. Seepage meter measurements were observed at slough 11, and side channel 10 was visited briefly during the return to Talkeetna by boat.

3.3 AGENCY AND SUBCONTRACTOR CONTACTS

Following the site visit described above, a number of knowledgable individuals and organizations were contacted in order to obtain published and unpublished information which might be available, and to elicit any comments or suggestions which might affect future studies. Organizations contacted included R&M Consultants, the Alaska Power Authority, Trihey & Associates, AEIDC, U.S. Geological Survey, Alaska Geological and Geophysical Surveys, and the U.S. Fish and Wildlife Service.

3.4 DATA ANALYSES

3.4.1 Aquifer Properties

Results of aquifer tests and specific capacity data in the Talkeetna area have been obtained from USGS files. These data were used in standard hydrologic analyses for estimation of aquifer properties for the alluvial materials at that site. The resulting aquifer properties in the Talkeetna area are thought to be similar to those of the valley-fill materials further upstream, in the vicinity of the side sloughs. In both areas, the valley-fill materials of interest consist of modern flood plain materials or adjacent fluvial and glaciofluvial terrace deposits. Although the valley is somewhat wider in the Talkeetna area than in the study area further upstream, all of the Talkeetna-area wells are located within about one-half mile of the river (Exhibit 9).

Datapod hydrographs have been provided for mainstem stage and groundwater levels in wells at slough 9. The data are reproduced in Appendix A. Attempts have been made to interpret these data by applying published (9)[1/] techniques for estimating aquifer properties based on groundwater variations in response to stream stage variations.

1/ Refers to the numbers in "References" at the end of the text

3.4.2 Aerial Photograph Interpretation

Available aerial photographs have been interpreted to identify probable contacts between bedrock, glacial detritus, and alluvial materials. Locations of reported seeps and upwellings have been compared with the inferred surficial geology to seek any obvious relationships between geologic contacts and locations of groundwater discharge to sloughs.

3.4.3 Field Data Reduction

The reduction of available field data has involved the tabulation, plotting, and computer storage of selected data. Data collected during 1983 has been emphasized because of the variety of data available and the existence of relatively large amounts of continuous or partially-continuous data. Where possible, mean daily values of parameters such as water level, discharge, temperature, and precipitation have been plotted versus time, and the resulting graphs compared to ascertain possible correlations. Parameters suspected of being strongly correlated have been plotted against each other on linear and logarithmic paper to determine the probable functional form of any relationships between the variables. During the course of the statistical analyses discussed below, much of the 1983 data has also been input to computer files, basically in the form of time series, in order to facilitate the statistical analyses and other mathematical analyses. It must be recognized that much of the 1983 data is provisional and subject to change as the data are reviewed and further reduced. However, these data should still be adequate to illustrate major trends and interrelationships.

3.5 MATHEMATICAL MODELING

3.5.1 Data Correlations

A variety of statistical correlations of existing time-series data (water levels, discharge rates, temperatures, other water quality parameters) have been performed. These activities were conducted to attempt to ascertain significant correlations among the various parameters for which data are available.

In general, these activities have included autoregression of time series data to ascertain preexisting trends; transformation of data so that nonlinear regression analyses can be performed, including lagging the data with respect to time; and multiple linear regression of transformed and nontransformed data. Transformations of the data were based in part on knowledge of the general hydrological setting of each slough. The objective of these analyses was to ascertain significant relationships among variables such as slough discharge and temperature, mainstem discharge and stage, air temperature, mainstem water temperature, precipitation, etc.

3.5.2 Two-Dimensional Cross-Sections and Profiles

Simplified analytical models of flow and thermal transport in vertical sections normal to the river have been used in analyzing existing data for the slough hydrologic regime. Computer programs were prepared based on published analytical solutions to relevant flow problems (1, 7).

Simulations of the groundwater surface between the mainstem and the sloughs, and variation of that surface with variations in mainstem water levels, within a two-dimensional vertical section extending from the river to the slough, were conducted by applying the convolution integral approach outlined by Hall and Moench (7). Although this approach presumes symmetry with respect to the dimension normal to the vertical section, and is thus only an approximation, it is believed to provide a reasonable estimate of the relationship between variations in mainstem stage and groundwater levels. Similar analyses were carried out for groundwater temperature variations, by applying the convolution integral approach of Hall and Moench (7) to the coupled thermal and groundwater flow solution developed by Acres American (1).

4.0 RESULTS

4.1 HYDROGEOLOGIC SETTING

4.1.1 Regional Geology

The regional geologic setting of the Susitna River between Devil Canyon and Talkeetna has previously been described in several works (6, 8, 10), and those descriptions will not be repeated in detail here. However, basic characteristics of regional geology relevant to the present study are briefly discussed below for the sake of completeness.

As described by R&M Consultants (10),

> " all sloughs along the river are part of the modern floodplain of the Susitna River [which] consists predominately of cobbly sandy gravels with silty mantles in areas between and adjacent to the main channels. Above and immediately adjacent to the modern floodplain lie a series of fluvial and glaciofluvial terraces deposited... following the later Wisconsin glaciations of Southcentral Alaska. The terrace deposits generally consist of coarse sandy gravels overlain by a few feet of sandy silt and silt overbank deposits...The valley floors and side walls above the terraces are thought to consist of glacial tills composed of gravel, sand and silt... Older... glacial and glaciofluvial drift may underlie the terraces and modern floodplains. Bedrock underlies the unconsolidated materials at an undetermined depth."

Available geologic mapping (13, 16) suggests that the unconsolidated fluvial and glaciofluvial deposits are confined to a very narrow interval along the river valley, with consolidated bedrock located on both sides of the river between Devil Canyon and Talkeetna. Interpretation of aerial photographs suggests that the width of the valley-fill sediments in the reach between sloughs 11 (near Gold Creek) and 8A is relatively consistent, averaging approximately 3,000 feet.

4.1.2 Interpretation of Aerial Photographs

The following discussion of the slough environment has been inferred from aerial photographs of the Susitna River and sloughs, at a scale of approximately 1 inch = 1000 feet, and various project reports.

Sediments in the river and slough regions consist of materials deposited within the active channel of the Susitna river (channel sediments) and materials forming the valley walls (valley wall deposits). Valley wall deposits may include bedrock, terrace deposits formed during past higher river levels, and till deposits, which reportedly cap the entire region.

Side sloughs are generally found on the left descending bank, with mainstem flow generally, but not consistently, along the right descending bank. Side slough areas are generally well vegetated, except within the channel of the slough itself. Slough areas are generally contiguous with the valley wall area, although separated from the valley wall by the Alaska Rail Road which parallels the left descending bank of the Susitna River between Gold Creek and Talkeetna. The photographs were inspected for evidence of uniformity in paleo-channel width, as might be inferred from terrace or valley wall position. Lack of such uniformity could help explain any differences in hydraulic behavior among various sloughs. There was some consistency noted in channel width in the segment examined between Gold Creek and slough 8. At Gold Creek, the apparent paleo-channel widens substantially, perhaps as a result of Gold Creek flow and sediment contributions. The river appears to have adjusted to a pattern lying between that of a braided stream and that of a meandering stream. Relatively steep valley walls, perhaps resulting from terraces, are observed on the south and east shores (left descending bank) while the north and west shores (right descending bank) appear from the photographs to exhibit generally undulating topography, gently rising with distance from the river. However, field observations suggest that the right descending valley wall has about the same steepness as the left descending wall, particularly in the vicinity of slough 9. Many scars are evident in the channel fill materials forming the small islands and lowermost floodplains adjacent to the river. Vegetation is generally absent within these scars. These scars appeared to be dewatered at the time the photographs were taken, but may convey water at high mainstem flows or as a result of staging during periods of freeze up or ice break up.

Upwellings (groundwater discharge within the sloughs) may occasionally, but not consistently, be apparent on the photographs, as inferred from differences in color tone. Interpretation of aerial photography provides no discernible relationship among the locations of the areas of upwellings, and the river morphology, distribution of river sediments, or the floodplain configuration. At several sloughs there is a distinct boundary at the mouth of the slough, separating dark (probably clear, silt free) water discharging from the slough, from the gray (probably turbid) water of the mainstem. In some cases, a zone of mixing of these waters can be observed extending downriver within the mainstem.

4.1.3 Slough Runoff Estimates

One potential source of at least part of the discharge from individual sloughs is direct precipitation on the drainage area of the slough. Based on preliminary studies, Trihey (12) concluded that local surface runoff may contribute a greater portion of the clear water flow to a side slough than does groundwater upwelling during the ice-free period of the year. However, there are also some side sloughs which depend predominantly on groundwater throughout the year (Trihey, 12).

A more recent study of local runoff to selected sloughs has been performed by R&M Consultants. A memorandum report on that study is reproduced in Appendix B. General conclusions for sloughs 8A, 9, and 11 are summarized below.

Slough 8A

It appears that the basin of Slough 8A will absorb significant amounts of precipitation following long dry periods, but could respond rapidly to larger events. Estimated baseflow to the slough for the period September 28-October 3, 1983, was 1.5 cfs, approximately 10% of the total slough discharge during the period.

Slough 9

A high percentage of the discharge from Slough 9 during the period September 28-October 3, 1983, can be attributed to local runoff. This indicates rapid response to precipitation within the drainage basin of the slough. The estimated baseflow to the slough during the period September 28-October 3, 1983, was 5.73 cfs, about 48% of the total slough discharge during the period.

Slough 11

Slough 11 had very little response to precipitation during 1983. Response of slough discharge appears closely related to mainstem flow instead of to precipitation.

4.1.4 Groundwater Underflow Estimates

Based on estimates of aquifer properties (as discussed in more detail below) and the average downstream groundwater level gradient within the Susitna River Valley, an estimate has been made of the volumetric rate of groundwater transport in the downstream direction within the Susitna River alluvium. For an assumed hydraulic conductivity of 500 gallons per day (gpd) per square foot, a saturated thickness of 100 feet, an aquifer width of 3000 feet (including the active channel and the alluvial floodplain), and an average downstream groundwater level gradient of

0.003, the average rate of downstream transport of groundwater would be about 0.7 cubic feet per second (cfs). Even if this estimate is low by an order of magnitude, it would appear that regional groundwater transport within the Susitna River alluvium would not be sufficient to provide all of the groundwater discharge apparently observed in the various sloughs. This tends to support hypotheses that large proportions of the slough discharge may be derived from shallow lateral flow from the river, or local runoff from tributary streams, rather than regional groundwater underflow within the Susitna River valley-fill materials (Trihey, 12).

A second possible source of groundwater upwelling within the sloughs would be regional groundwater transport toward the Susitna River valley through the glacial till and sedimentary bedrock forming the valley walls. Although no local hydrologic data are available for these formations, an estimate of potential groundwater flow through them has been based on formation properties for similar materials reported in the literature, and estimates of the local hydraulic gradient and saturated aquifer thickness.

Davis and DeWiest (5) have summarized formation properties for a wide variety of aquifer materials. They report typical hydraulic conductivity values of about 2×10^{-6} cm/sec for glacial till, and about 8×10^{-6} for sedimentary bedrock. For purposes of the present analysis, a value of 5×10^{-6} cm/sec was assumed for the hydraulic conductivity of the valley wall materials. Although no data are available regarding depth to water within the valley wall materials, the groundwater level surface within natural materials generally reflects the land surface. Thus, the land surface slope toward the Susitna River valley, which averages about 0.3 in the vicinity of sloughs 8A and 9, has been taken as an approximation of the hydraulic gradient. Finally, the effective saturated thickness of groundwater flow through the valley wall materials toward the river has been assumed to be 500 feet.

All of the above approximations and assumptions have been selected so as to provide an estimate of the maximum groundwater flow through the valley wall materials. Based on these assumptions, the potential groundwater inflow into the river valley from the adjacent valley walls would be about 2.5×10^{-5} cfs per linear foot of valley length. This would provide about 0.2 cfs of discharge to either of sloughs 8A or 9, and a total inflow of only 4 cfs to the entire Susitna River valley in the reach between sloughs 21 and 8A. These estimates of the maximum potential inflow to sloughs 8A and 9 from the valley wall materials are about an order of magnitude less than the inferred groundwater upwelling component of slough discharge, as discussed below. These results again tend to support hypotheses that large proportions of slough discharge may be derived from shallow lateral flow from the river, or local runoff from tributary streams.

Another aspect of groundwater underflow was considered by referring to the maps of groundwater contours at sloughs 8A and 9 for various dates in 1982 presented by R&M Consultants (10, Figures 3.4 through 3.21). Assuming homogeneous and isotropic aquifer materials, groundwater flow lines were drawn normal to the water level contour lines shown on those maps. The flow lines suggested flow from a side channel of the river toward a portion of the right descending bank in the upper reaches of slough 8A (see, e.g., Exhibit 10), and toward slough 9B and a portion of the left descending bank in the upper reaches of slough 9. Assuming the same saturated thickness and hydraulic conductivity as noted above, the groundwater discharge through each inferred flow tube (see Exhibit 10) was calculated. By summing the discharges within the several flow tubes, an estimate was obtained of the total groundwater discharge to that reach of the slough fed by the several flow tubes. This was converted to a unit flow by dividing by the total length of slough bank at the terminus of all of the flow tubes.

Only limited discharge measurements were available for slough 8A in 1982. The R&M Consultants stage recorder was influenced by backwater effects from a beaver dam, and thus could not be used to reliably estimate slough discharge. ADF&G obtained three discharge measurements from slough 8A in 1982 (E.W. Trihey, personal communication, March 1984), but none was on a date for which groundwater level data were measured. Consequently, the calculated unit flows (i.e., discharge per length of slough bank) were compared with mainstem discharge at the Gold Creek gage for dates for which sufficient data were available to estimate the unit flows (Exhibits 11, 12). The upstream berm at Slough 8A is not believed to have been overtopped on any of these dates, since the mainstem discharge was less than 30,000 cfs on each date. As can be seen from Exhibit 11, there is no obvious correlation between the discharge per unit bank length and the mainstem discharge. However, from Exhibit 12 it appears that there might be a time-series correlation with a possible lag of a few days between the two discharges (i.e., in early September, the unit slough discharge increases as the mainstem discharge increases, while in early October a decrease in mainstem discharge is followed several days later by a decrease in unit slough discharge). However, no definite conclusions can be drawn from this very limited set of data. In order to be more definite, we would require more frequent (e.g. daily) measurement of groundwater levels at enough points to prepare water-level elevation maps, so that variations in groundwater flow rates could be compared with mainstem stage or discharge.

Using a similar approach, estimates of the total groundwater discharge to sloughs 9 and 9A were compared with measured discharge from slough 9 for two dates on which both slough discharge had been calculated and groundwater level maps had been prepared. For June 23, 1982, when the mainstem discharge at Gold Creek was 25,000 cfs and the slough 9 berm was overtopped, the estimated slough discharge was 1.44 cfs and the measured discharge was 180 cfs. For October 7, 1982, when the mainstem discharge at Gold Creek was 8,480 cfs, the estimated slough discharge was 1.43 cfs and the measured discharge was 1.0 cfs. No definite conclusions can be drawn from these limited observations, except that the approximate calculated groundwater discharge toward slough 9 appears to be of the same order of magnitude as the observed discharge from the slough during conditions of relatively low flow on the mainstem. In order to be more definite, we would require more frequent (e.g. daily) measurement of both slough discharge and groundwater levels at enough points to prepare water-level elevation maps, so that variations in groundwater flow rates could be compared with slough discharge.

4.2 AQUIFER PROPERTIES

4.2.1 Talkeetna Pumping Test

In March of 1981, a 100-foot deep well was constructed at the Talkeetna Fire Hall. A constant-rate pumping test of the well was performed on March 10-11, 1981, by Dowl Engineering. The well was pumped at a constant rate of 310 gallons per minute (gpm) for a period of twenty-nine hours, and water levels were periodically measured in the well. Water levels in the pumping well stabilized within about an hour, and remained essentially constant for the duration of the test.

The pumping test data were obtained during a search of U.S.G.S. files in Anchorage. The data were plotted on semi-logarithmic and full-logarithmic paper, and standard analyses were conducted (14, 15). The Jacob straight-line analysis of the semi-logarithmic data plot (Exhibit 13) yielded a transmissivity of approximately 13,900 gpd/ft during the early period of the test, before stabilization of water levels in the well. The full-logarithmic data plot could not be matched by either the Theis or Hantush type curves, so no aquifer properties could be inferred in this manner.

Assuming a saturated thickness of approximately 22 feet based on well logs, the calculated transmissivity for this test would give a hydraulic conductivity of approximately 630 gpd/ft^2.

The stabilization of water levels in the pumped well indicates some kind of recharge to the tested aquifer, as a result of delayed yield from storage, leakage from overlying or underlying water-bearing units, or induced infiltration from the river. Well logs indicate that the unit tested is probably confined (artesian), so delayed yield from storage by gravity drainage is unlikely. The inability to match the field data with the Hantush leaky-artesian type curves suggests that leakage is also relatively unlikely. The well is located approximately one-quarter to one-third mile from the river (Exhibit 9). Thus, the most probable cause of the water-level stabilization is induced infiltration from the river, suggesting hydraulic connection between the aquifer and the river. However, the actual cause of this phenomenon can be neither confirmed nor quantified because of the lack of observation well data during the test.

4.2.2 Talkeetna Specific Capacity Data

Aquifer transmissivity can also be estimated from specific capacity data (the ratio of total water level drawdown to pumping rate) collected during well drilling and testing. Such data are available for six wells in the Talkeetna area (see Exhibit 9), and have been obtained from U.S.G.S. files. Utilizing graphs presented by Walton (14, 15), the estimated transmissivity determined from these data ranges from 2,400 to 11,000 gpd/ft assuming water table conditions, and from 4,400 to 22,000 gpd/ft assuming artesian conditions. The results are summarized on Table 1.

Five of the six wells for which specific capacity data are available are less than 27 feet deep, and thus would be expected to exhibit water-table conditions in this environment. The sixth well is that at the Talkeetna Fire Hall, which is 100 feet deep and screened in materials which would be expected to exhibit artesian conditions during a relatively short specific capacity test. By dividing the estimated transmissivity by the original saturated thickness in each well, hydraulic conductivity values ranging from 167 to 1,000 gpd/ft^2 are obtained, with a mean of 424 gpd/ft^2. This compares quite favorably with the value of 630 gpd/ft^2 inferred from the pumping test data at the Talkeetna Fire Hall.

4.2.3 Slough 9 Surface Water - Groundwater Correlation

Attempts have been made to estimate aquifer properties from correlations of river stage and groundwater level variations at slough 9. The data, for the period May 23 to June 12, 1983, are presented in Appendix A. This is the only period for which surface water and groundwater levels were simultaneously monitored at adjacent locations appropriate for application of published techniques for inferring hydraulic conductivity. The data were analyzed according to methods described by Pinder et al. (9). However, the field data could not be matched to the theoretical type curves generated by the methods of Pinder et al. (9), regardless of the values assumed for aquifer properties. In general, the field data curves had substantially different slopes than the theoretical curves for all values of aquifer diffusivity (Exhibit 14). In particular, data from borehole 9-5 showed a more rapid rise early in time, but a substantially lower peak value, than predicted by the theory (Exhibit 14).

It appears that the hydrologic conditions affecting the wells near slough 9 are considerably different than those assumed in the theory. The theory is based on the assumption that all recharge to the aquifer during passage of a flood peak on the river is derived from lateral inflow from the river to the aquifer. At slough 9, it is possible that groundwater levels are also affected by regional water level variations, possibly by groundwater underflow originating far upriver from the slough or from the bedrock areas southeast of the slough, or by direct infiltration of precipitation. Unfortunately, little precipitation data for the period May 23 - June 12, 1983, is available (see Appendix C). It is also possible that the groundwater level data were affected by recharge both from the mainstem and from the slough, since the slough 9 berm was overtopped during much of the summer of 1983. During the period May 23-June 12, 1983, the mainstem discharge exceeded 23,000 cfs, and the upstream berm at slough 9 was presumably overtopped, on 9 of the 21 days (each day of the period May 30-June 7, see Appendix D). The beaver dam located near the mouth of slough 9B could also affect local groundwater conditions, particularly near borehole 9-5, by raising local groundwater levels and perhaps moderating the influence of variations in river stage.

4.3 DATA CORRELATIONS

A variety of correlations between slough and mainstem data have been attempted. These have included merely comparing graphs of time-series data, plotting variables versus each other on linear, semi-logarithmic and full logarithmic paper, and utilizing a standard statistical analysis computer program to perform multiple linear regression and cross-correlation analyses of transformed and raw data. In general, the analyses conducted to date have employed mean daily values of relevant parameters.

The more formal linear regression and cross-correlation analyses which have been conducted have used the MINITAB computer program developed at Pennsylvania State University. MINITAB is a general purpose statistical computing system, including recently-implemented routines for time series analysis based on techniques described by Box and Jenkins (4). The fairly wide usage of MINITAB, and its bases in standard statistical techniques, confer a considerable degree of reliability on results of its application.

4.3.1 Slough Discharge Data

A variety of correlations have been drawn between slough discharge data for sloughs 8A, 9, and 11 and several other parameters such as mainstem discharge, mainstem stage, water temperature, and precipitation. No general relationships encompassing all the sloughs have been observed. In many important respects, the three sloughs for which most data are available behave differently.

Provisional USGS mainstem discharge data are reproduced in Appendix D, and discharge data for sloughs 8A, 9, and 11 are given in Appendix E. General relationships between slough and mainstem discharge are illustrated by Exhibits 15-17, which show discharge versus time for the mainstem at Gold Creek (Appendix D) and for sloughs 8A, 9, and 11 (Appendix E). There generally appears to be a correspondence at least between major peaks in the slough and mainstem discharge measurements. For example, the higher mainstem flows observed in early June, early August, and late August are fairly well reflected in the data from sloughs 8A and 9 (Exhibits 15 and 16). However, the discharge at slough 8A does not appear to reflect variations in mainstem flow between about June 5 and August 5. Field observations indicate that slough 8A was not overtopped during the 1983 open-water season, so these observed variations in slough 8A discharge may result largely from local storm runoff to tributary streams. The slough 9 discharge appears to correlate very well with even less significant variations in mainstem discharge. This would be expected, however, because the slough 9 berm was overtopped approximately half the time period reflected in Exhibit 16, so slough 9 actually acts as a side channel to the mainstem during much of this period. Slough 11 exhibits relatively little variation in discharge, but there does appear to be a good correspondence between variations in mainstem discharge and in Slough 11 discharge (Exhibit 17).

Plots of slough discharge versus mainstem discharge for the summer of 1983 are presented in Exhibits 18-20. Linear regression equations for selected fits to the data are summarized on Table 2. Slough 8A discharge appears generally not to be correlated with mainstem discharge (Exhibit 18a). Since slough 8A was reportedly not overtopped during this period of record, the very high slough discharge values at mainstem discharge in excess of 35,000 cfs may merely represent dates of high storm runoff to slough 8A and its tributary streams. However, recent information suggests that slough 8A berms might in fact be overtopped at mainstem discharges in excess of 30,000 cfs (E.J. Gemperline, personal communication, May 1984)). Removing such points from the linear regression does not, however, improve the correlation (Exhibit 18a and Table 2).

Exhibit 18b shows slough 8A discharge versus mainstem discharge for the period June 6 through August 7, 1983. This is a period during which relatively little variation in slough discharge was observed (see Exhibit 15). These data can be fit by a linear regression equation with relatively large R^2 (coefficient of determination) if values of slough discharge greater than 3 cfs are excluded. The resulting regression line must not be considered too definitive, since it is based on excluding approximately one-third of the data points.

Exhibit 19a shows slough discharge versus mainstem discharge for slough 9. In general, there is no apparent single correlation which would apply to all the data. Exhibit 19b, however, shows slough 9 discharge versus mainstem discharge, excluding dates when the mainstem discharge exceeded 16,000 cfs and the slough 9 upstream berm was overtopped (E.J. Gemperline, personal communication, May 1984). With the exception of two data points, there is an excellent correlation between these data.

In contrast to the data for sloughs 8A and 9, a plot of Slough 11 discharge versus mainstem discharge exhibits a linear form with a positive slope (Exhibit 20). This is consistent with observations that Slough 11 was not overtopped during the summer of 1983 and receives very little storm runoff. Discharge from Slough 11 thus appears to be fairly directly related to mainstem discharge.

In general, utilizing MINITAB routines, the discharge at slough 11 correlates fairly well with mainstem discharge or stage, with correlation coefficients in excess of 90% for linear regressions with slough 11 discharge as the dependent variable. Multiple linear regression involving parameters such as temperature or precipitation had only slightly higher correlation coefficients than when mainstem discharge or stage was the only independent variable. In contrast, linear regressions involving slough 8A discharge as the dependent variable exhibited correlation coefficients of the order of 25 - 55%. Addition of other parameters increased the values of these correlation coefficients, but that may represent only the effect of correlating two time series which exhibit similar seasonality in their variations. Linear regressions involving slough 9 discharge as the dependent variable exhibited correlation coefficients in the range of 65 to 90%. However, these regressions generally included mainstem discharge as an independent variable, without eliminating periods of overtopping, and thus are biased since slough 9 was overtopped during much of the summer of 1983. Cross-correlation analyses of time-series data did not indicate any significant time lags between mainstem and slough discharges.

It is perhaps noteworthy that slough 11, whose discharge is most readily correlated to that of the mainstem, is perhaps the simplest of the three sloughs studied in detail. The surface drainage area directly contributing to this slough is extremely small, so that slough discharge includes relatively little storm runoff. Furthermore, the aerial photograph interpretation discussed above noted that the river valley seems to widen considerably at Gold Creek, just above slough 11, and to maintain a fairly consistent width in the vicinity of sloughs 8A through 11. Thus, it may be that groundwater recharge from the mainstem becomes substantially more significant below Gold Creek than above Gold Creek because of this change in morphology.

The linear regression equations for fits to the data shown on Exhibits 18-20 are summarized on Table 2. A few observations regarding those equations can be made. In the first place, both 1982 and 1983 data for slough 11 can be represented by essentially the same line. This tends to lend credence to the linear regression fit to the data shown on Exhibit 20. Furthermore, the linear regression fit to the data shown on Exhibit 18b, representing most of the data for the period June 6 through August 7, 1983, at slough 8A, has approximately the same slope as that shown on Exhibit 20. This suggests that the slough 8A discharge at very low flow is related to mainstem discharge in approximately the same way as is discharge at slough 11. Finally, the linear regression fit to the slough 9 data, excluding periods of overtopping (Exhibit 19b), exhibits a relatively large coefficient of determination (R^2), but a slope approximately three times those of the best linear fits to data from sloughs 8A and 11. This suggests that slough 9, absent overtopping, responds more rapidly to variations in mainstem discharge than do sloughs 8A and 11. One possible explanation might be that, as a result of the extensive periods of overtopping, subsurface materials in the vicinity of slough 9 exhibit a higher degree of saturation and perhaps higher water tables, so that variations in mainstem discharge are more readily translated into upwellings of groundwater within the slough, rather than just variations in groundwater levels.

4.3.2 Seepage Meter Data

Nine seepage meters were monitored at four different sloughs during the summer of 1983. Two meters were located at each of sloughs 8A, 11, and 21, and three meters were located at Slough 9 (see Exhibit 2 for approximate locations). Each seepage meter consists of an open-bottomed container submerged within a slough and covering an area of slough-bottom sediment. A bag attached to the container is evacuated, and the time required to fill the bag is measured. The rate of flow into the bag is taken as a measure of the rate of flow through the slough-bottom sediment into (or out of) the bottom of the container, as described by R&M Consultants (10).

The seepage meter data collected during the summer of 1983 are summarized in Appendix F. Plots of measured seepage rate versus mainstem discharge are presented on Exhibits 21-29. The seepage meter data are generally consistent with the slough discharge correlations discussed above. The seepage rates at meters 8-1, 8-2, 9-1, 11-1 and 11-2 are generally positively correlated with mainstem discharge, although the data are somewhat scattered about the regression fits to the data except for those from the slough 11 meters (Exhibits 21-23). However, seepage rates at meters 9-2 and 9-3 seem to be uncorrelated with mainstem discharge (Exhibits 24 and 25). At slough 11, the seepage rates at meters 11-1 and 11-2 are very well correlated with mainstem discharge (Exhibits 26 and 27). This tends to confirm the previous observations that upwelling at slough 11 is derived rather directly from mainstem recharge to the local groundwater aquifer.

Seepage meter data at slough 21 (Exhibits 28 and 29) suggest that this slough is substantially different from those below Gold Creek. Seepage rates appear to be negatively correlated to mainstem discharge at meter 21-1, with seepage rates decreasing as mainstem discharge increases. At seepage meter 21-2, there appears to be no correlation between seepage rates and mainstem discharge. At slough 21, the river valley is narrower and the valley walls somewhat steeper than further downstream. Thus, a relatively high proportion of the groundwater discharge at this slough may originate from infiltration of precipitation on the surrounding uplands, or recharge from the river relatively far upstream from the slough, rather than groundwater underflow from the river immediately adjacent to the slough. If groundwater discharge at Slough 21 did originate as recharge from the river relatively far upstream from the slough, then seepage rates at the slough would be expected to correlate well with mainstem discharge, with a time lag reflecting the travel time from the river to the slough. In order to confirm such a hypothesis, it would be necessary to monitor seepage rates on a more frequent basis than has been done to date, for example on a daily basis, preferably during a period of rapidly rising river stage.

4.3.3 Temperature Data

Analyses of temperature data have been limited to considering plots of daily mean temperatures at various points, primarily using 1983 data. Limited plots of slough temperature versus mainstem temperature have also been made. These analyses have used provisional 1983 temperature data provided by the Alaska Department of Fish and Game. These data are subject to revision, and some error may even have been introduced during our reduction of the data. Nonetheless, it is believed that the present data are sufficient to illustrate general trends in the water temperature data, and thus support the following discussion.

At slough 8A, data are primarily available from intragravel and surface water measuring points at the middle and in the upper reaches of the slough (Exhibits 30 and 31). The intragravel data from different points show essentially the same behavior, with temperatures gradually rising from about 3°C in early May to about 5° C in late July, and then fairly rapidly falling to about 4° in late August (Exhibit 31)). Temperatures in the middle of the slough are generally higher than those at the upper end of the slough, except in the latter half of July. The intragravel temperatures generally appear to be subdued reflections of the surface water temperatures at corresponding points. However, surface water temperatures for the middle of the slough exhibit greater variations, rising as high as 14° C in late July (Exhibit 31b). Surface water temperatures at the upper end of the slough only rise to about 7.5 °C, but show the same general trends as at the middle of the slough. Since this slough was reportedly not overtopped during the 1983 period of temperature record analyzed, the high temperatures observed in the surface water at the middle of the slough can probably be attributed to solar heating, rather than surface water discharge as a result of overtopping. It should also be noted that the maximum surface water temperature at river cross-section LRX 29 during the summer of 1983 was also about 14 °C in late July, comparable to the maximum slough surface water temperature (Exhibit 31b).

At slough 9, data are available for surface water and intragravel measuring points within the slough, surface water and intragravel measuring points on the mainstem, and from three groundwater wells (Exhibit 32). The mainstem temperatures, as well as the surface water temperatures within the slough, show essentially the same behavior: winter temperatures are near zero; temperatures begin to increase in mid-May and reach maximums of about 13° in late June, and persist through July; temperatures then fall to near zero by late September. Mainstem intragravel temperatures (not plotted on Exhibit 32) are similar to the surface water temperatures, with the intragravel temperature about a degree higher than the surface water temperature at the mainstem during late September and October of 1983. In contrast, the intragravel measurements at slough 9 remain essentially constant at about 3.5°C from mid-March through late August, with temperatures exceeding 4°C on only two occasions, and falling to 3° only once (Exhibit 32b).

The groundwater data (Exhibit 32a) show considerably more variation than the slough intragravel data (Exhibit 32b). At borehole 9-1A, which is nearest to the river, temperatures reached a low of about 2.5 ^{o} in late February, and then rose to over 5^{o} in early September. At borehole 9-5, near slough 9B, temperatures fell from 4^{o} in early January to 2.5^{o} during April, and then rose to about 5.5^{o} in early October before again falling. At borehole 9-3, temperatures were relatively stable, varying between 3.5^{o} and 4.5^{o}. However, in general, during the winter period January to May, temperature variations in 9-3 were opposite those in the other two wells, rising when they were falling, and vice versa. During the summer, temperatures in all three wells generally rose (Exhibit 32a).

In very general terms, the groundwater temperatures at slough 9 appear to be very subdued reflections of surface water temperatures in the vicinity of slough 9, with peak groundwater temperatures lagging peak surface water temperatures by two to four months. However, it has not been determined whether the groundwater temperatures actually reflect changes due to the infiltration of river water into aquifer materials, or whether the groundwater merely reflects seasonal variations in parameters such as air temperature or solar radiation. Intragravel temperatures in Slough 9 appear to be independent of the groundwater temperatures.

No attempt has been made to isolate periods of overtopping in analyzing the temperature data for slough 9. The slough 9 surface water temperatures appear to be essentially the same as the mainstem surface water temperatures for the period May through August, 1983 (Exhibit 32b). The slough 9 intragravel temperatures appear to be independent of the mainstem or slough surface water temperatures (Exhibit 32b). Groundwater temperatures appear to vary somewhat with changes in mainstem or slough temperatures. However, the attenuative capacity of the groundwater regime is probably sufficient to mask any effects of overtopping, and thus invalidate any attempts to isolate such effects.

At slough 11, data are available for surface water and intragravel measuring points within the slough, and surface water measuring points on the mainstem (Exhibit 33). The intragravel temperature within the slough is rather uniform, increasing slightly from about 3°C in January to 3.5°C in early May, and then remaining essentially constant through late August. The surface water temperature within the slough is approximately the same as the intragravel temperature through late April, but then increases and varies between 5 and 7°C from May through August. There is no apparent relationship between mainstem and slough water temperatures, in striking contrast to the fairly strong correlation between mainstem and slough discharge at slough 11.

At slough 21, data are available for surface water and intragravel measuring points on the mainstem and at the mouth and in the upper reaches of the slough (Exhibit 34). Intragravel temperatures at the mouth of the slough were approximately constant at 3.5°C from January through April, then gradually increased to almost 4°C by late August (Exhibit 34a). Intragravel temperatures in upper reaches of the slough varied around 3°C from January through April, but then increased to about 6.5°C from early June through mid-August, with considerable temperature variation (Exhibit 34b). In the upper reach of slough 21, intragravel temperatures were essentially the same as surface water temperatures at comparable points. Near the mouth of the slough, surface water temperatures varied considerably, while intragravel temperatures remained essentially constant (Exhibit 34a). Mainstem intragravel temperatures were generally higher than surface water temperatures (Exhibit 34a).

4.4 Analytical Models

Limited mathematical modeling of groundwater levels and temperatures has been performed during this study. No attempt was made to actually simulate groundwater discharge to the sloughs, or the temperature of such discharge. The basic objective of this modeling was to investigate the rate at which changes in mainstem stage or temperature might be propagated toward the sloughs through the groundwater regime. To this end, some simple one-dimensional analytical models were applied.

4.4.1 Groundwater Level Variations

As described by Hall and Moench (7), flow and head variations in stationary linear stream-aquifer systems can be simulated by application of the convolution integral. Head fluctuations in a semi-infinite aquifer due to an arbitrarily varying flood pulse on the stream can be expressed as an integral involving the stream stage and various aquifer properties. The integral solution can then be expressed in approximate form by a finite series which is convenient for computer evaluation.

In its simplest form, the solution presented by Hall and Moench (7) can be expressed as follows:

$$h(x,t) = \int_0^t F(\tau)U(x, t-\tau)d\tau , \qquad (1)$$

where h(x,t) is the groundwater elevation at distance x from the stream and at time t since the simulation began; F(t)=H(t), the river stage at time t; and U(x,t), the instantaneous unit impulse response function of Hall and Moench (7), is given by

$$U(x,t)=x \exp(-x^2/4\alpha t)/[(4\pi\alpha)^{1/2} t^{3/2}] \qquad (2)$$

where α is the aquifer diffusivity, given by the ratio of transmissivity to storage coefficient. Equation (1) can be approximated by the finite series

$$h(x,t) \approx \sum_{k=1}^{i} F(k)U[x, (i-k+1)\Delta t] \Delta t \qquad (3)$$

A computer program has been written to evaluate equation (3) for a variety of values of the input parameters. In general, it has been assumed that the aquifer hydraulic conductivity is 500 gpd/ft^2, aquifer thickness is 100 feet, and the storage coefficient varies between 0.0002 for artesian conditions and 0.2 for water table conditions.

Exhibit 35 shows the simulated groundwater level as a function of time at various distances from the river. The surface water hydrograph utilized was the water level at the Susitna River sidechannel above slough 9 for the time period May 25 through June 10, 1983 (Appendix A). Five data points per day were interpolated from graphs of the side channel stage during that period. The observed water level variations at boreholes 9-1A and 9-5 have also been plotted on Exhibit 35. It is interesting to note that the observed groundwater levels are most closely matched by simulated curves for artesian conditions (Exhibit 35a), rather than water table conditions (Exhibit 35b). However, the data for borehole 9-1A, located about 700 feet from the river, are most closely matched by the simulated water level at a distance of about 2000 feet from the river, while the data for borehole 9-5, located about 1500 feet from the river, are most closely matched by the simulated water level at a distance of about 1000 feet from the river. As noted previously, water levels at borehole 9-5 are probably affected by slough 9B and the beaver dam at the mouth of 9B, and thus would not be expected to readily fit the present theory. These results suggest that the groundwater aquifer in the vicinity of borehole 9-1A may behave somewhat as an artesian aquifer rather than a water table aquifer. However, logs of wells in the vicinity of slough 9 presented by R&M Consultants (10) indicate water table conditions. It is possible that local overbank silt deposits or relatively thin layers of fine-grained materials may act to partially confine coarser water-bearing layers in the area, thus resulting in localized or short-term hydraulic behavior as an artesian aquifer.

Exhibits 36 through 39 show the simulated groundwater level as a function of distance away from the river for various times and various values of aquifer diffusivity. These figures generally illustrate that as diffusivity gets larger (i.e., the storage coefficient gets smaller), the effects of variations in river stage are more rapidly propagated into the aquifer toward adjacent sloughs. For example, Exhibit 39 shows that for fully artesian conditions, small variations in river stage could be very quickly transmitted, as a pressure wave, a distance of over 4000 feet into the aquifer within one day. Thus, for fully artesian conditions, changes in river stage could influence groundwater upwelling to the sloughs almost instantaneously. On the other hand, Exhibit 36 suggests that for water table conditions, variations in river stage might not have an appreciable effect on groundwater conditions except very near the river. Consequently, under water table conditions, variations in river stage might not be expected to significantly affect average groundwater upwelling to the sloughs unless the areas of upwelling were relatively near the river.

4.4.2 Temperature Variations

Groundwater temperature variations have been considered by a process similar to that used to analyze water level variations. Acres American (1) presented an analysis of coupled thermal and groundwater flow for a single square-wave temperature pulse representing the average river water temperature. By applying the convolution integral approach of Hall and Moench (7), the analysis of Acres American (1) can be extended to consider shorter time frame variations in river temperature.

Equation (1) can again be applied, with F(t) now being given by the river water temperature. According to Hall and Moench (7), the instantaneous unit impulse response function U(x,t) can be derived from the unit step response function P(x,t) by differentiation with respect to time. P(x,t) is essentially the solution given by Acres American (1),

$$T(x,t) = 0.5 \text{ erfc } [(x-v_r t)/2(Dt)^{1/2}] \tag{4}$$

where T(x,t) is the groundwater temperature at time t and distance x away from the river due to a unit step increase in river water temperature (1); v_r is the average retarded velocity of the mean temperature, which accounts for heat exchange between the groundwater and the soil skeleton of the aquifer (1); and D is the coefficient of hydrodynamic dispersion, which accounts for the temperature dissipation as a result of mechanical dispersion during transport through the porous medium (1).

Results of this analysis generally confirmed the results of the similar study performed by Acres American (1): as a result of heat transfer and mechanical dispersion during flow through the groundwater regime, short-term variations in river temperature are rapidly damped. Consequently, by the time groundwater has traveled from the river to a nearby slough, its temperature could easily be approximately equal to the mean annual river temperature. This conclusion is consistent with the observations noted previously that slough intragravel temperatures, which probably represent the temperature of upwelling groundwater, are relatively constant throughout the year, and are approximately equal to mean annual river water temperature. Consequently, long-term changes in the mean annual river water temperature would probably result in changes in the heat input to the aquifer, and thus changes in the upwelling groundwater temperature.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 GENERAL CONCLUSIONS

The results of the present study do not permit a single model to be formulated which can describe the discharge and temperature variations which are observed at each of the various sloughs studied. The hydraulic and thermal behavior of each slough is substantially different from that of the other sloughs studied. The discharge at slough 11 seems to correlate very well with mainstem discharge, while the discharge at slough 9 is largely controlled by mainstem overtopping of the berm and the discharge at slough 8A may be complicated by factors such as surface runoff and groundwater underflow from sources other than the mainstem of the Susitna River. However, where it has been possible to remove the effects of some of these complicating factors and isolate attention on only the groundwater upwelling contribution to slough discharge, fairly good correlations between slough discharge and mainstem discharge have been observed. In very general terms, based on available information, it appears that variations in the groundwater contribution to slough discharge at sloughs 8A, 9, and 11 might be reasonably represented by 0.0001 to 0.00035 of corresponding variations in mainstem discharge at Gold Creek.

Regardless of the complicating factors affecting discharge from each slough, the available data suggest that the temperature of upwelling groundwater remains fairly constant throughout the year, at a temperature approximately equal to the mean annual (time-weighted, not discharge-weighted) mainstem temperature. This study has tended to confirm previous conclusions that heat exchange between groundwater and soil materials, and mechanical dispersion during groundwater transport through the aquifer, are reasonable mechanisms to account for the observed groundwater temperatures.

5.2 EFFECTS OF PROJECT OPERATION

The results of the present study do not permit any detailed projections to 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 might 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. This could require extensive additional field studies at each slough, and additional office analyses. However, some general conclusions can be drawn based on the results of this study.

Some sloughs, such as slough 11, will probably respond fairly directly to changes in mainstem discharge. Slough 11 is generally characterized by a lack of tributary streams and rare overtopping of its upstream berm. Sloughs with similar environmental features might be expected to respond similarly to changes in mainstem discharge. Slough 11 discharge is correlated fairly well with mainstem discharge, so any long-term increase or decrease in mainstem discharge could result in a similar increase or decrease in average slough discharge. Any such relationship for slough 11 could be approximated by the linear regression fit to the data presented in Exhibit 20, but the scatter in those data might result in fairly wide error bounds.

Some sloughs, such as slough 9 during the summer of 1983, are overtopped during much of the time as a result of high river stage or ice staging. Such sloughs might be effectively considered as side channels of the river, rather than sloughs, during such periods. To the extent that the mainstem flow which will result in overtopping of the berms of a particular slough is known, projections of project flows can be used to estimate what proportion of the time such sloughs will carry predominantly mainstem flow (at mainstem temperatures), rather than groundwater discharge. However, project flow conditions will be characterized by lower than normal summer discharge, and higher than normal winter discharge, so the frequency of overtopping will be reduced. Slough 9 discharge under project conditions might be estimated from appropriate curve fits to the data presented in Exhibit 19.

Most sloughs will probably be similar to slough 8A in that it will not be possible to separately determine each factor contributing to the discharge of the slough without conducting additional field investigations at each such slough. It is probable, however, that for sloughs which are as complicated as slough 8A, the contribution to slough discharge as a result of groundwater underflow originating at the river will be small enough that project variations in mainstem discharge will not significantly affect the slough discharge under most conditions. However, it is not possible with present information to either confirm or quantify any such relations. A complete water balance for the slough would be required, including estimates of storm runoff to the slough, based on studies similar to those discussed in Appendix B.

Temperatures of groundwater discharge to the sloughs appear to be reasonably approximated by the mean annual (time-weighted) river temperature. It is likely that any variations in mean annual river temperature as a result of project operation will also result in a similar change in the temperature of groundwater upwelling to the sloughs, to the extent that such upwelling is derived from the mainstem (e.g., as is probably the case at slough 11). Similarly, for sloughs such as slough 9, which may be more frequently overtopped, any changes in mainstem temperature will also result in similar changes in the mainstem flow which is diverted down the slough during overtopping. This could induce downwelling of river water during overtopped periods, which would have some influence on the average temperature of groundwater which is discharged to the slough. However, as noted above, overtopping will be much less frequent during project operation than under present conditions.

5.3 RECOMMENDATIONS

Results of the present study have provided some preliminary conclusions regarding relationships between mainstem discharge and temperature variations and corresponding variations in groundwater upwelling rates and temperatures in selected Susitna River side sloughs. The recommended studies described below are designed to strengthen and refine these preliminary conclusions.

5.3.1 Additional Field Studies

One additional field study which might provide significant additional information with a relatively small investment of project resources would be additional attempts at aquifer testing, utilizing existing wells. Available data indicates that no successful aquifer testing has been conducted at any of the project well locations on the Susitna River below Devil Canyon. Falling head permeability tests were reportedly attempted at the deeper wells at slough 9, but the tests were not successful because of the high permeability of the material tested. Successful testing of these wells might require sustained pumping or injection at a relatively high rate for a period of several hours or days. This would require the use of pumping equipment, electrical generating equipment to operate the pump, and probably fuel for a generator. Such aquifer tests, or additional attempts at falling head tests, constant head tests, or similar in-situ permeability testing, could help confirm the nature of local aquifer materials (e.g., water table or partially confined) and quantify the degree of hydraulic connection between the river and the groundwater aquifer. Such knowledge could help refine present estimates of the rates at which changes in mainstem hydraulic or thermal river conditions are propagated through the groundwater regime toward the sloughs.

Water levels in existing deep wells and in selected shallow wells should continue to be monitored at slough 9, along with open-water stages on the mainstem, side-channels and sloughs. Using the results from the aquifer testing and water level monitoring, estimates can then be made of the theoretical temporal variations of groundwater flow into slough 9. The estimates can be verified by conducting a water balance study of slough 9. Precipitation can be measured at the Sherman Station, with accumulating precipitation cans located at other portions of the basin in order to determine the spatial distribution of precipitation, including orographic effects. Evaporation can be estimated from data gathered at Watana Camp. Streamflow should be continuously monitored in the slough and in the tributary which enters slough 9 approximately halfway upstream from the mouth. Frequent discharge measurements should be made to establish reliable rating curves.

Additional seepage meters might also be installed in both slough 9 and slough 11 to determine the relationship between seepage rates and mainstem discharge at Gold Creek. Frequent readings should be made at each seepage meter, so that variations in seepage rates can be compared with variations in mainstem and slough discharge. All visible upwelling locations should also be mapped.

Collection of contemporaneous samples of river water, groundwater from wells, slough intragravel water, and slough surface water might be made. Analysis of samples should be conducted for major anions and cations (Ca, Mg, K, Na; Cl, SO_4, CO_3, HCO_3), as well as parameters significant to salmon spawning and incubation (e.g., temperature, DO, conductivity). Monthly sampling for several months is suggested, to ascertain trends (at least during the summer season). The objectives of these analyses would be to seek water quality parameters other than temperature which may be diagnostic of the rate of groundwater transport from the mainstem and the amount of groundwater discharge to sloughs.

5.3.2 Additional Data Analyses

Analyses discussed in this report should be continued and refined, once final 1983 data reports have been prepared. It is recommended that additional analyses should concentrate on removing the effects of overtopping from slough 9 discharge data, and refining estimates of storm runoff to sloughs 8A and 9. In this manner, groundwater contributions to slough discharge can be more accurately estimated, and compared with mainstem discharge records.

The 1983 groundwater data presented in Appendix G should be reassessed in light of refined estimates of groundwater discharge to slough 9. If possible, those data should be supplemented by estimates of surface water stage in the side channel near borehole 9-1A, as well as in slough 9B and slough 9 near the mouth of slough 9B, in order to help clarify groundwater level variations in response to surface water fluctuations.

The environment of critical habitat sloughs should be reviewed in order to identify those sloughs which are characterized by factors such as frequent overtopping or significant tributary inflow. Such classification of sloughs can help guide the amount of emphases to be place on proposed additional studies.

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NO.	TITLES

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TABLE 1. TRANSMISSIVITY ESTIMATES BASED ON SPECIFIC CAPACITY DATA FOR TALKEETNA WELLS

WELL DESIGNATION[1]	WELL DEPTH (ft)	REPORTED SPECIFIC CAPACITY (gpm/ft)	PUMPING PERIOD (hrs)	INFERRED TRANSMISSIVITY (gpd/ft)[3] ARTESIAN (S=0.0001)[4]	WATER TABLE (S=0.2)
A[2]	17	6.0	4	10,200	6,400
		6.76	16	14,000	8,000
B	16	2.65	8	5,000	2,600
C	16	2.14	16	4,400	2,400
D	100	11.5	2	22,000	11,000
E	24	3.33	2	5,400	2,500
F	26	3.33	2	5,400	2,500
			MEAN VALUES	9,500	5,100

NOTES:

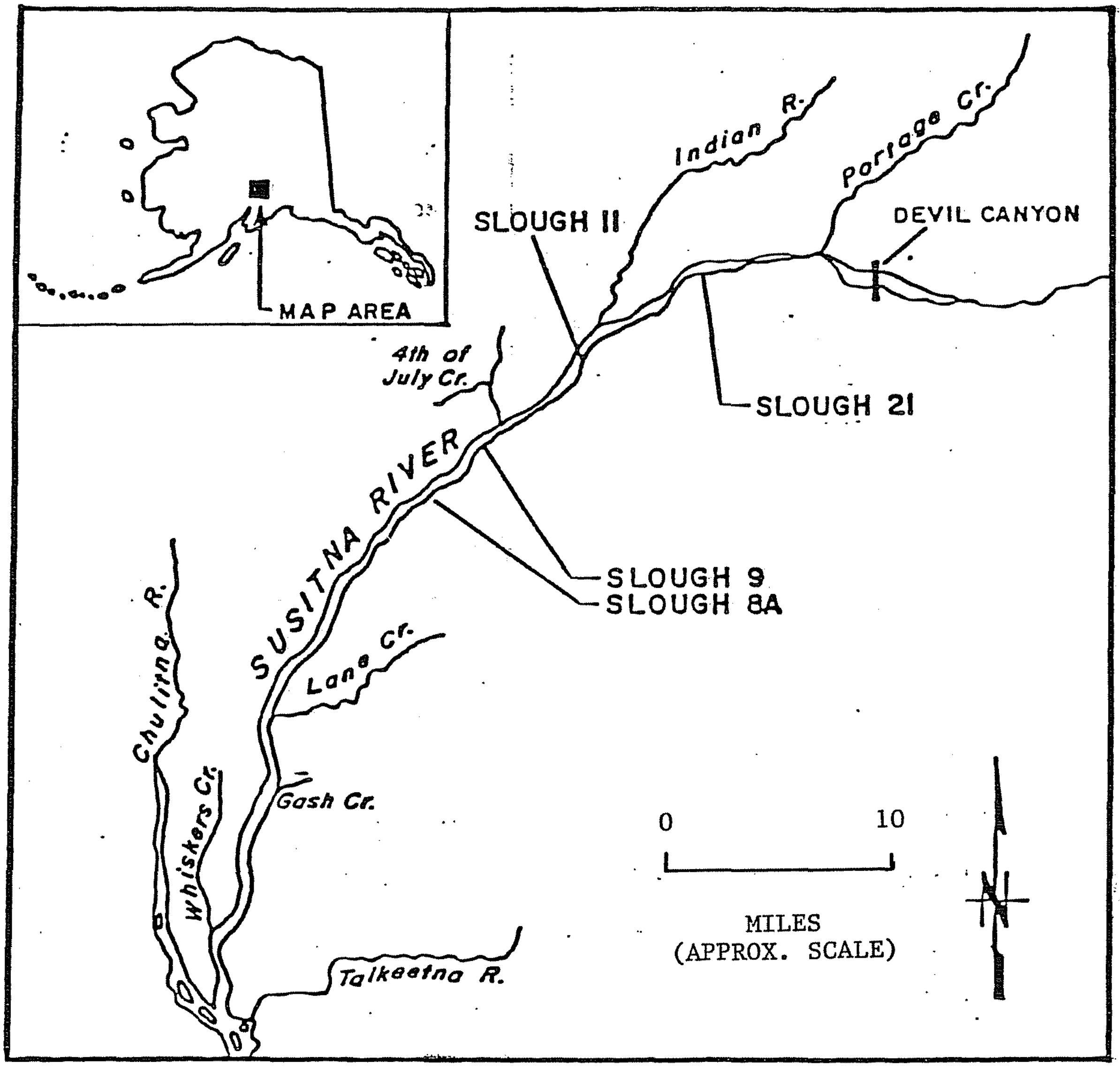
(1) See Exhibit 9 for approximate locations.
(2) Two tests for Well A.
(3) Based on Walton (13, 14)
(4) S = assumed storage coefficient for aquifer condition noted.

TABLE 2. LINEAR REGRESSION EQUATIONS FOR SLOUGH DISCHARGE VS. MAINSTEM DISCHARGE

SLOUGH	YEAR	REGRESSION EQUATION *	R^2	EXHIBIT **	COMMENTS
8A	1983	$S = -3.81 + 0.000525\ G$	0.103	18a	All data points
	1983	$S = 5.04 + 0.000040\ G$	0.002	18a	Excluding G > 30,000 (8 data points)
	1983	$S = -0.629 + 0.000128\ G$	0.632	18b	June 6 through August 7 only; excluding S > 3 (20 data points)
9	1983	$S = 1.97 + 0.000351\ G$	0.805	19b	Excluding dates when upstream berm overtopped (G > 16,000); excluding S > 8 (2 data points)
11	1982	$S = 2.16 + 0.000105\ G$	0.497	None	All data points
	1983	$S = 1.52 + 0.000102\ G$	0.765	20	All data points
21	1982	$S = -7.55 + 0.00105\ G$	0.542	None	All data points

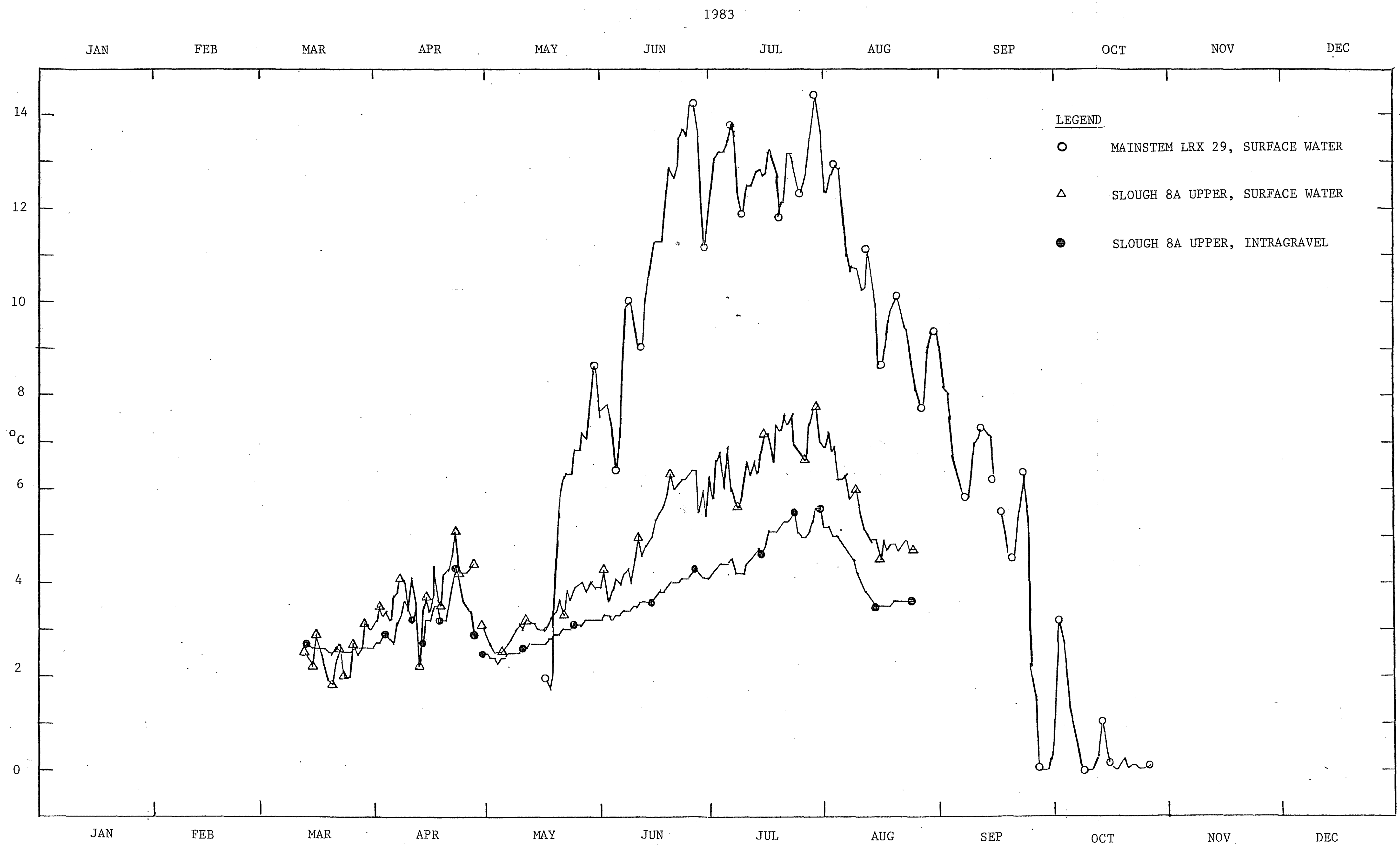
Notes: * S = Slough Discharge, cfs; G = Mainstem Discharge at Gold Creek, cfs.

** Refers to exhibit where linear regression fit is displayed.



SOURCE: MODIFIED FROM ADF&G (2)

EXHIBIT 1. LOCATIONS OF PRINCIPAL SLOUGH STUDY SITES, 1982-1983.



SOURCES: ADF&G (3)
ADF&G PROVISIONAL 1983 DATA

EXHIBIT 31a. SLOUGH 8A WATER TEMPERATURES, 1983

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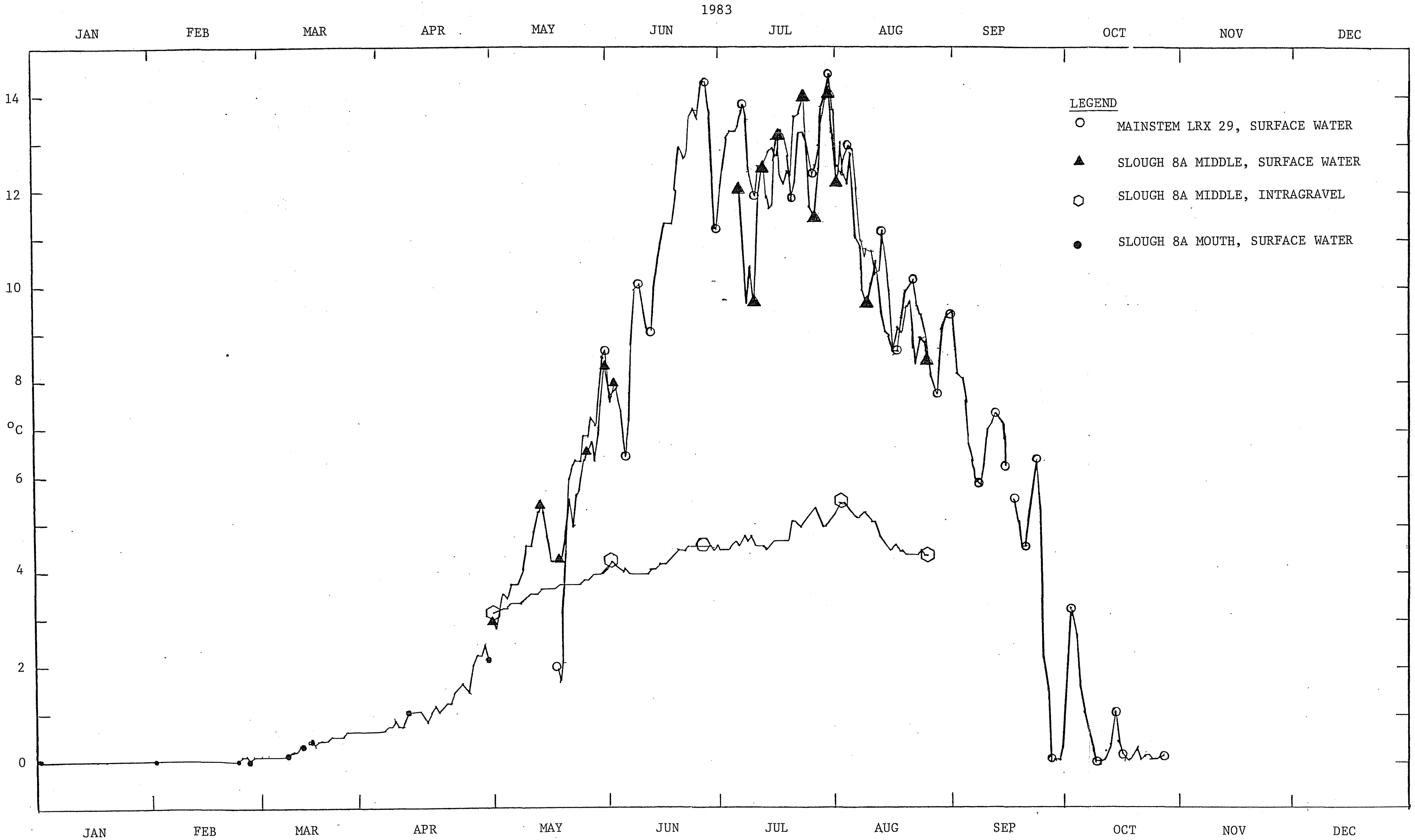

SOURCES: ADF&G (3)
ADF&G PROVISIONAL 1983 DATA

EXHIBIT 31b. SLOUGH 8A WATER TEMPERATURES, 1983

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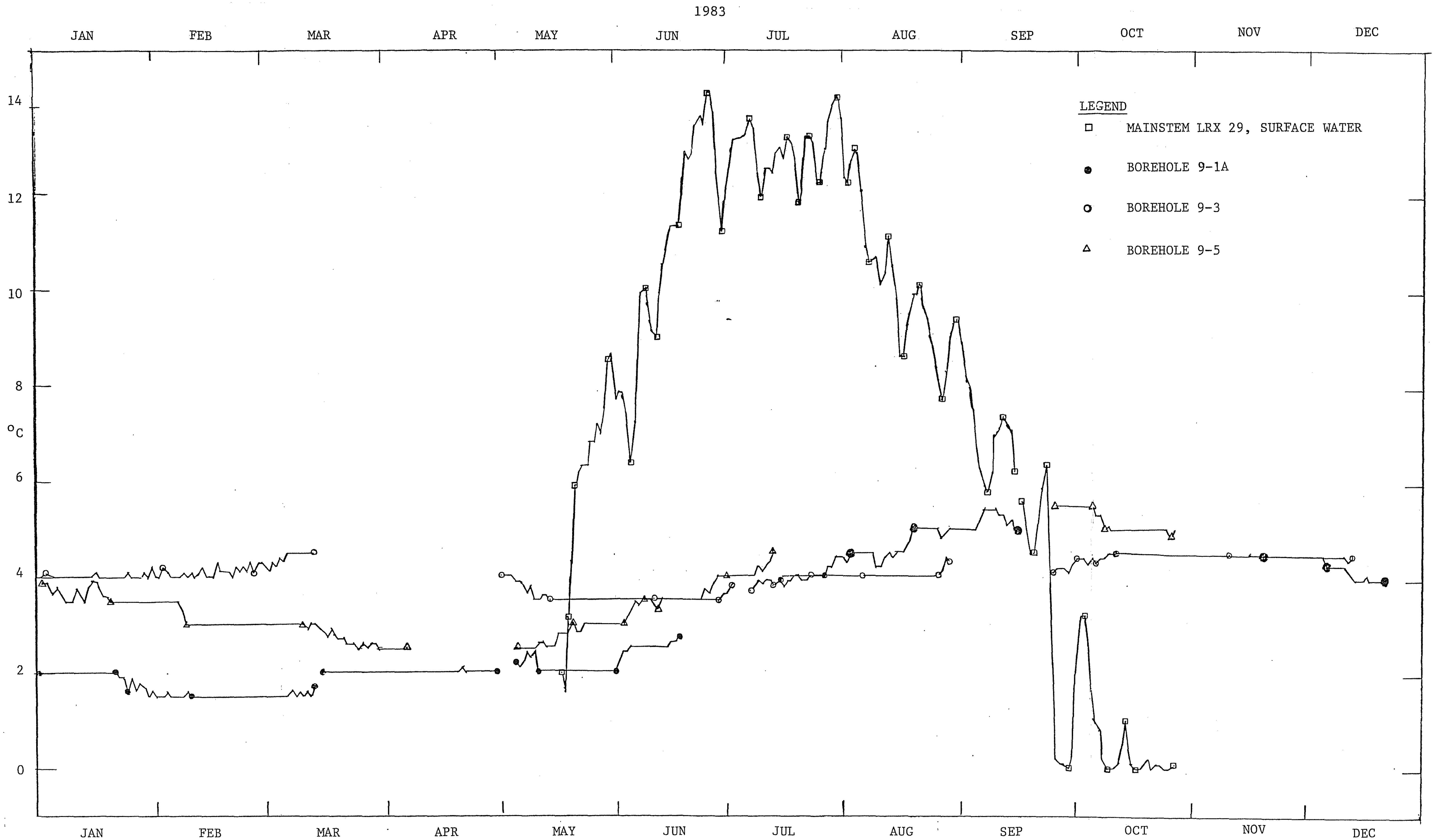
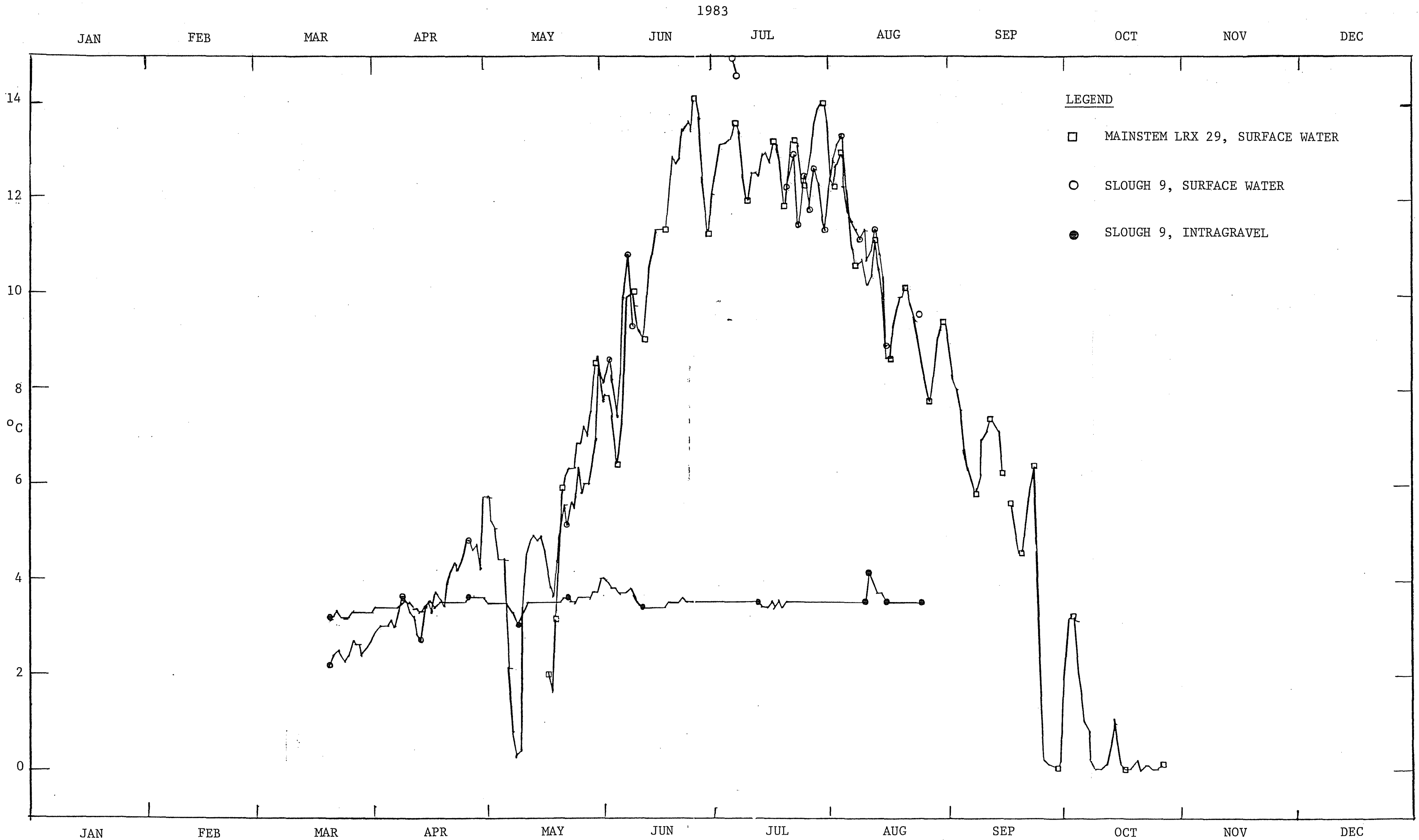
SUSITNA JOINT VENTURE



SOURCES: ADF&G (3)
ADF&G PROVISIONAL 1983 DATA
R&M CONSULTANTS PROVISIONAL 1983 DATA

EXHIBIT 32a. SLOUGH 9
WATER TEMPERATURES, 1983

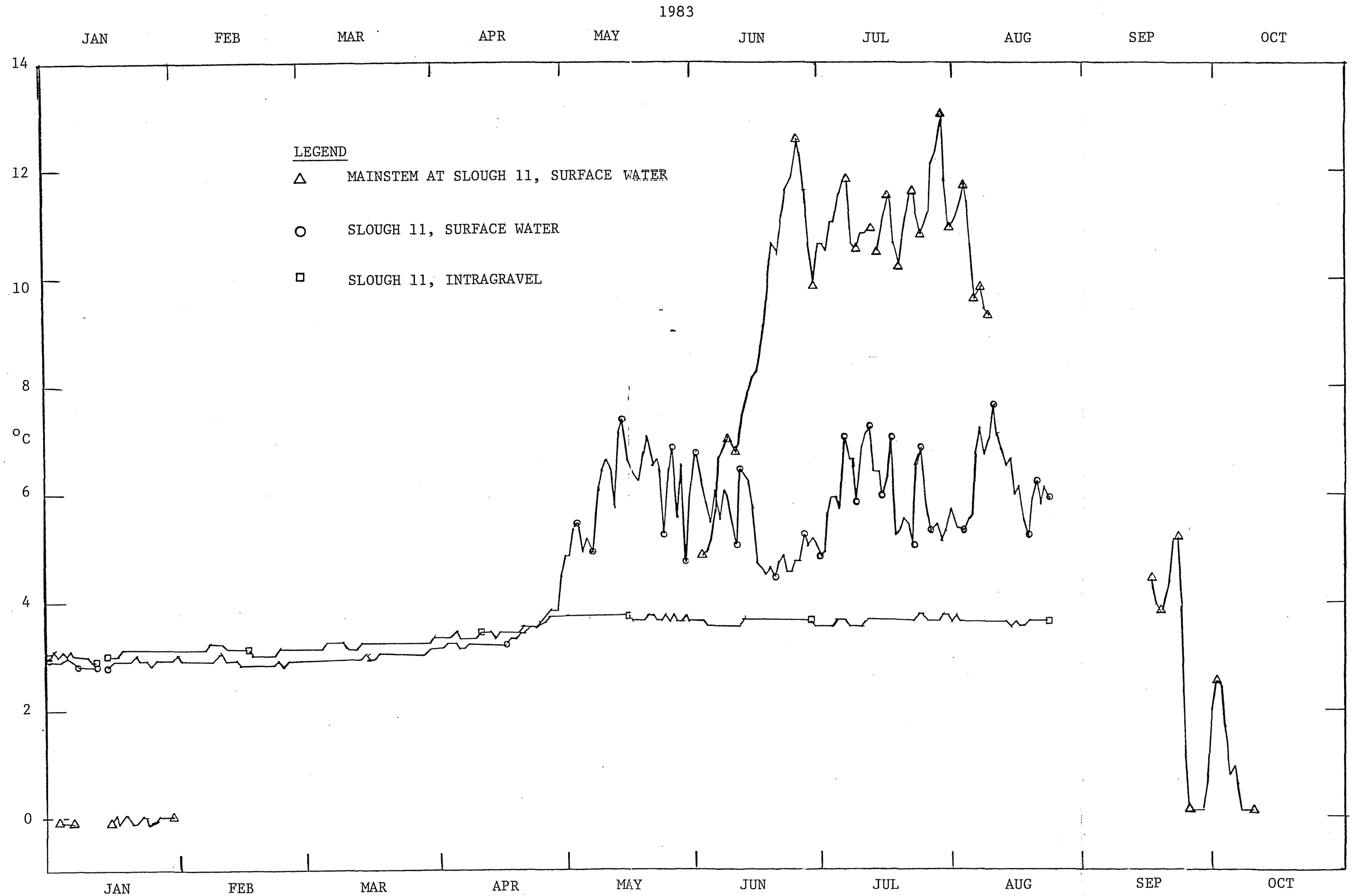
HARZA-EBASCO
SUSITNA JOINT VENTURE



SOURCES: ADF&G (3)
ADF&G PROVISIONAL 1983 DATA

EXHIBIT 32b. SLOUGH 9
WATER TEMPERATURES, 1983

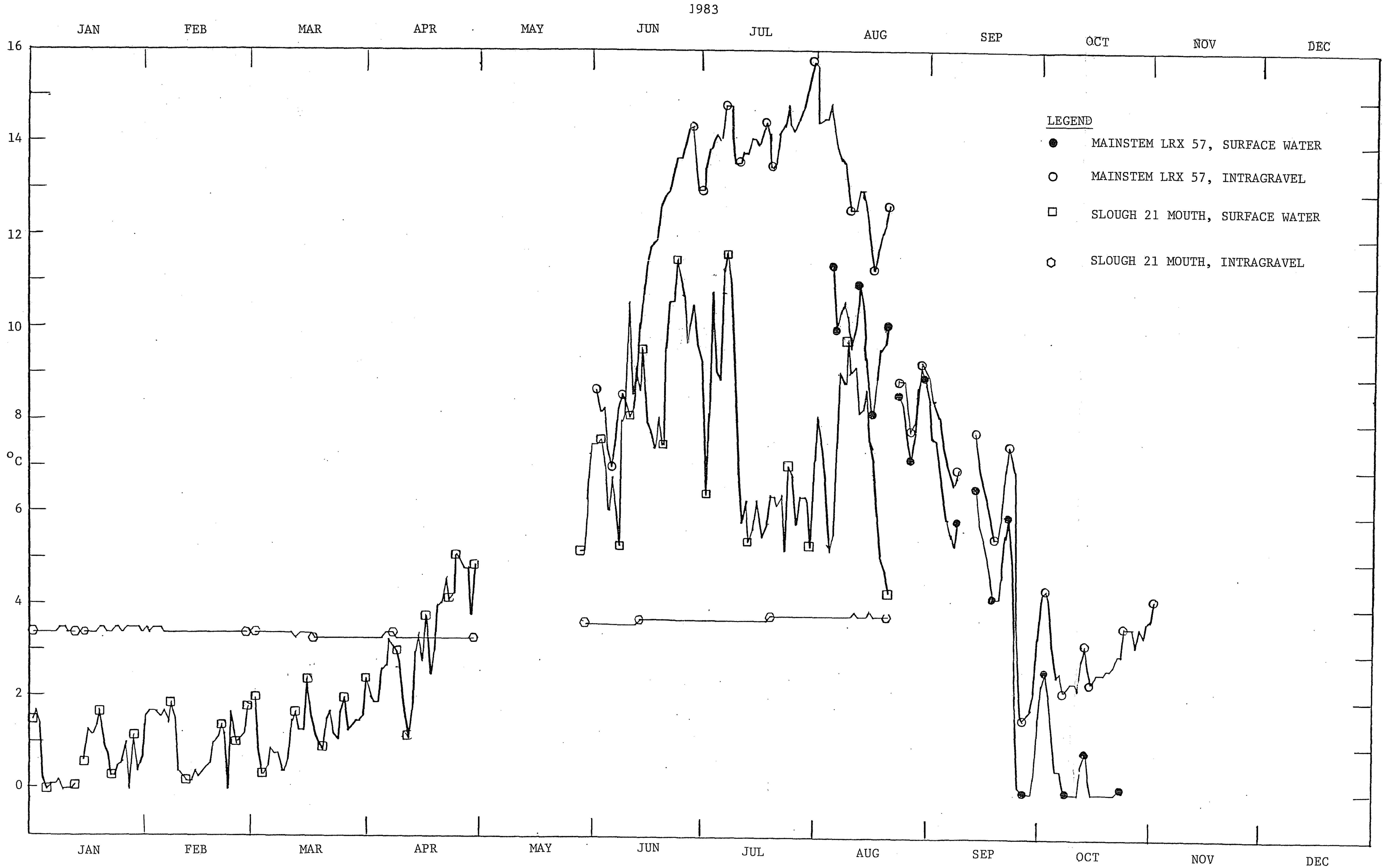
HARZA-EBASCO
SUSITNA JOINT VENTURE



SOURCES: ADF&G (3)
ADF&G PROVISIONAL 1983 DATA

EXHIBIT 33. SLOUGH 11
WATER TEMPERATUES, 1983

HARZA-EBASCO
SUSITNA JOINT VENTURE



SOURCES: ADF&G (3)
ADF&G PROVISIONAL 1983 DATA

EXHIBIT 34a. SLOUGH 21
WATER TEMPERATURES, 1983

HARZA-EBASCO
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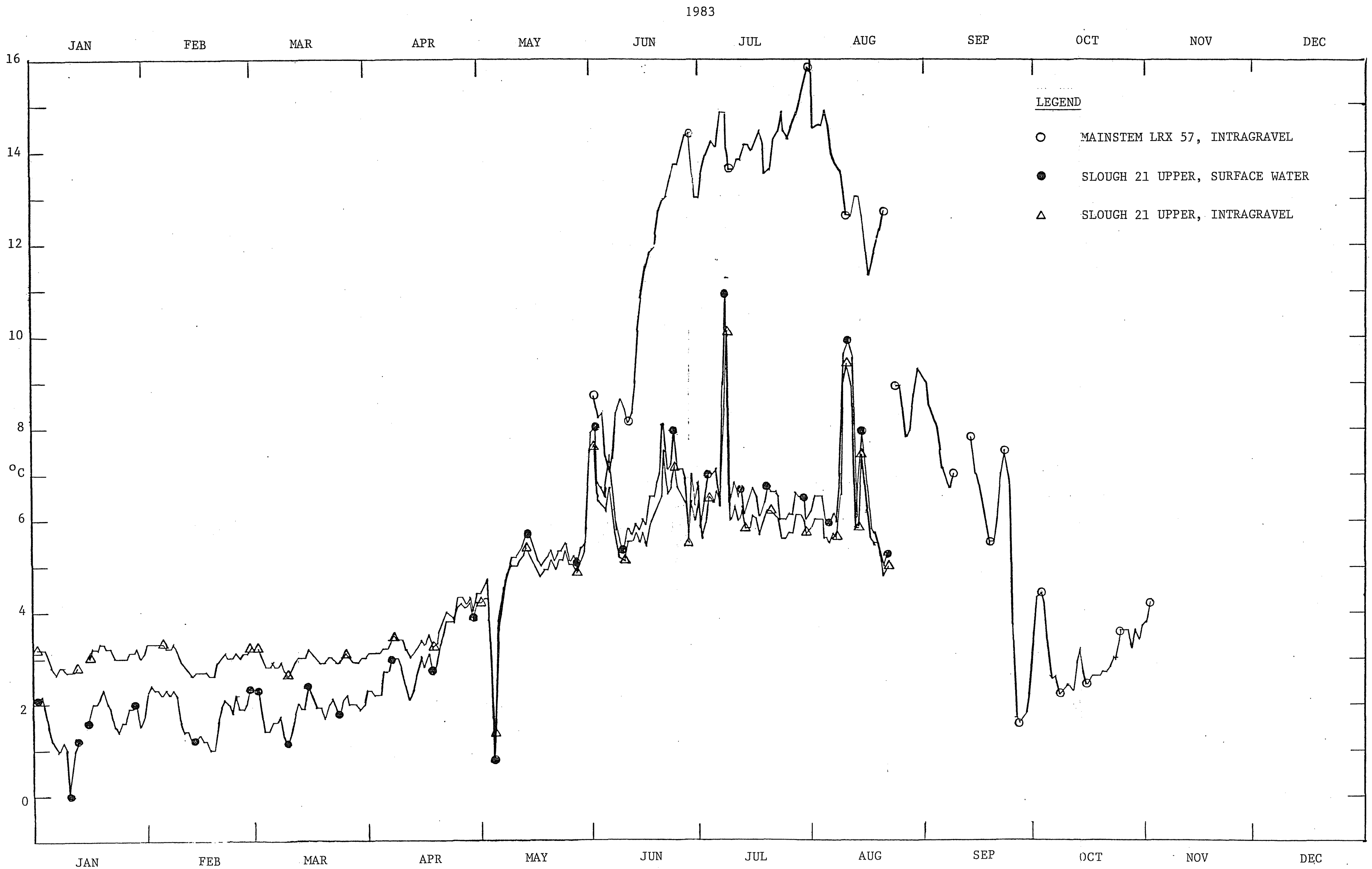

SOURCES: ADF&G (3)
ADF&G PROVISIONAL 1983 DATA

HARZA-EBASCO
SUSITNA JOINT VENTURE

EXHIBIT 34b. SLOUGH 21
WATER TEMPERATURES, 1983

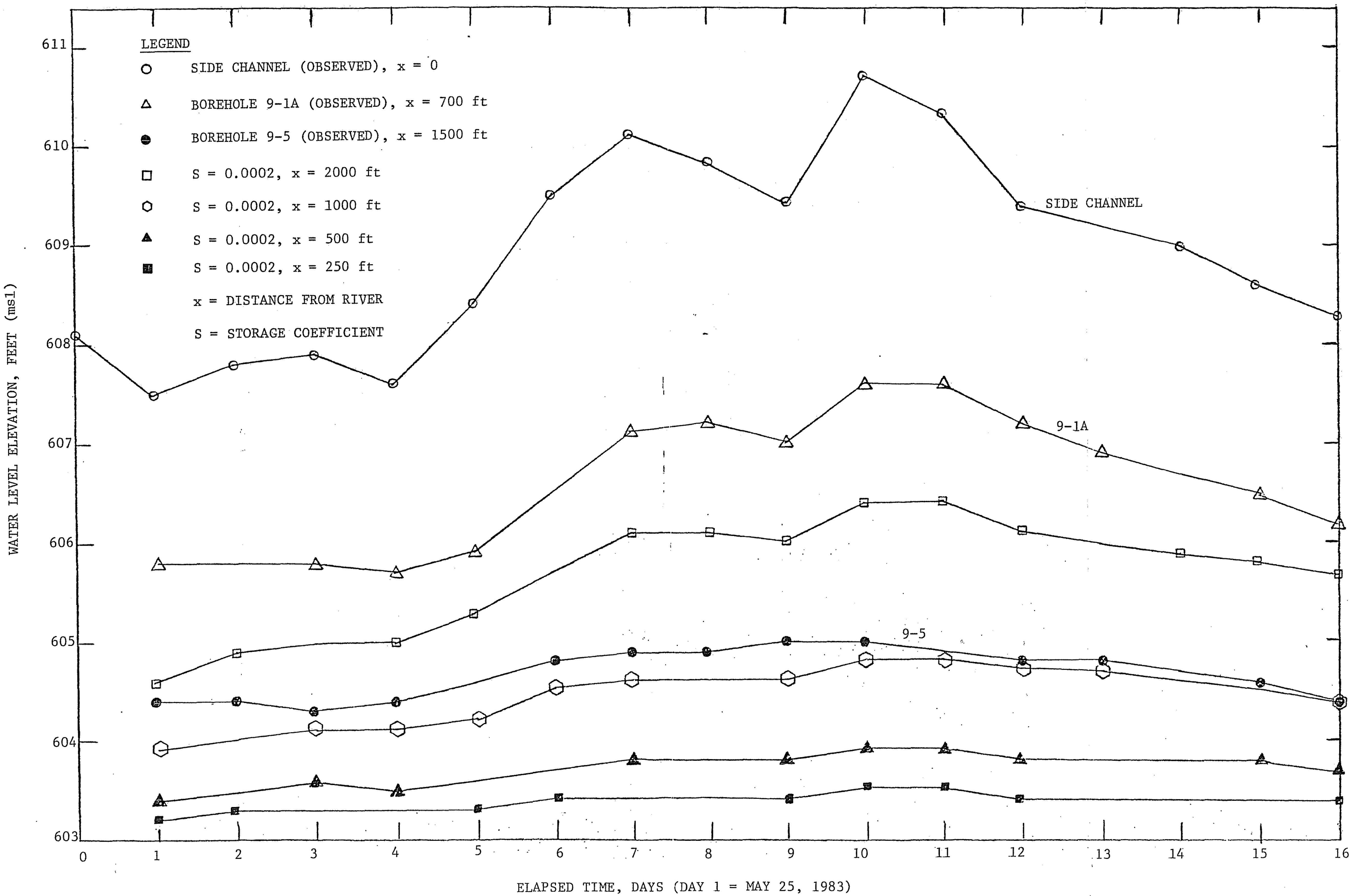

EXHIBIT 35a. SIMULATED GROUNDWATER LEVEL VARIATIONS IN RESPONSE TO RIVER STAGE VARIATIONS

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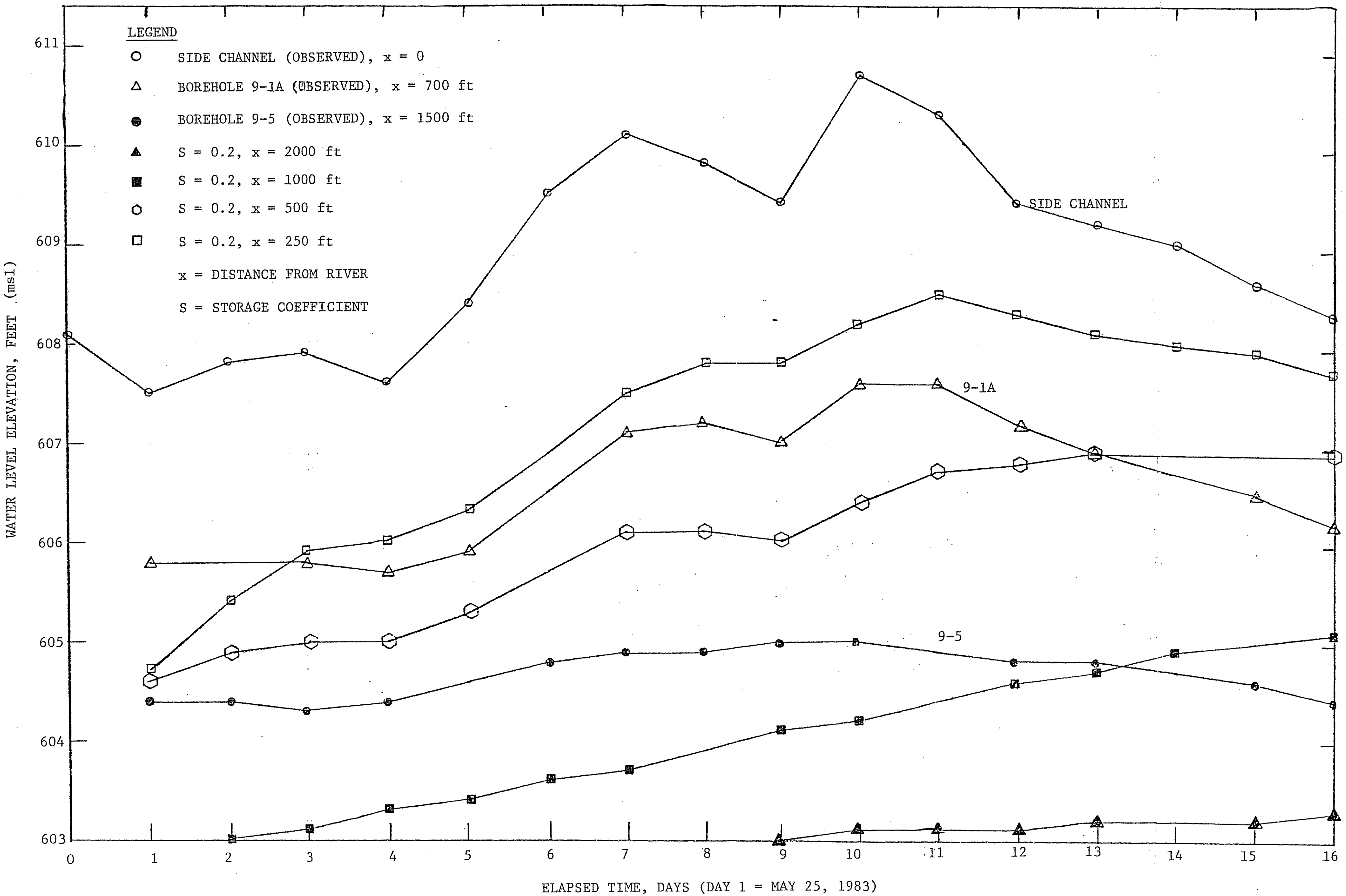

EXHIBIT 35b. SIMULATED GROUNDWATER LEVEL VARIATIONS IN RESPONSE TO RIVER STAGE VARIATIONS

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SUSITNA JOINT VENTURE

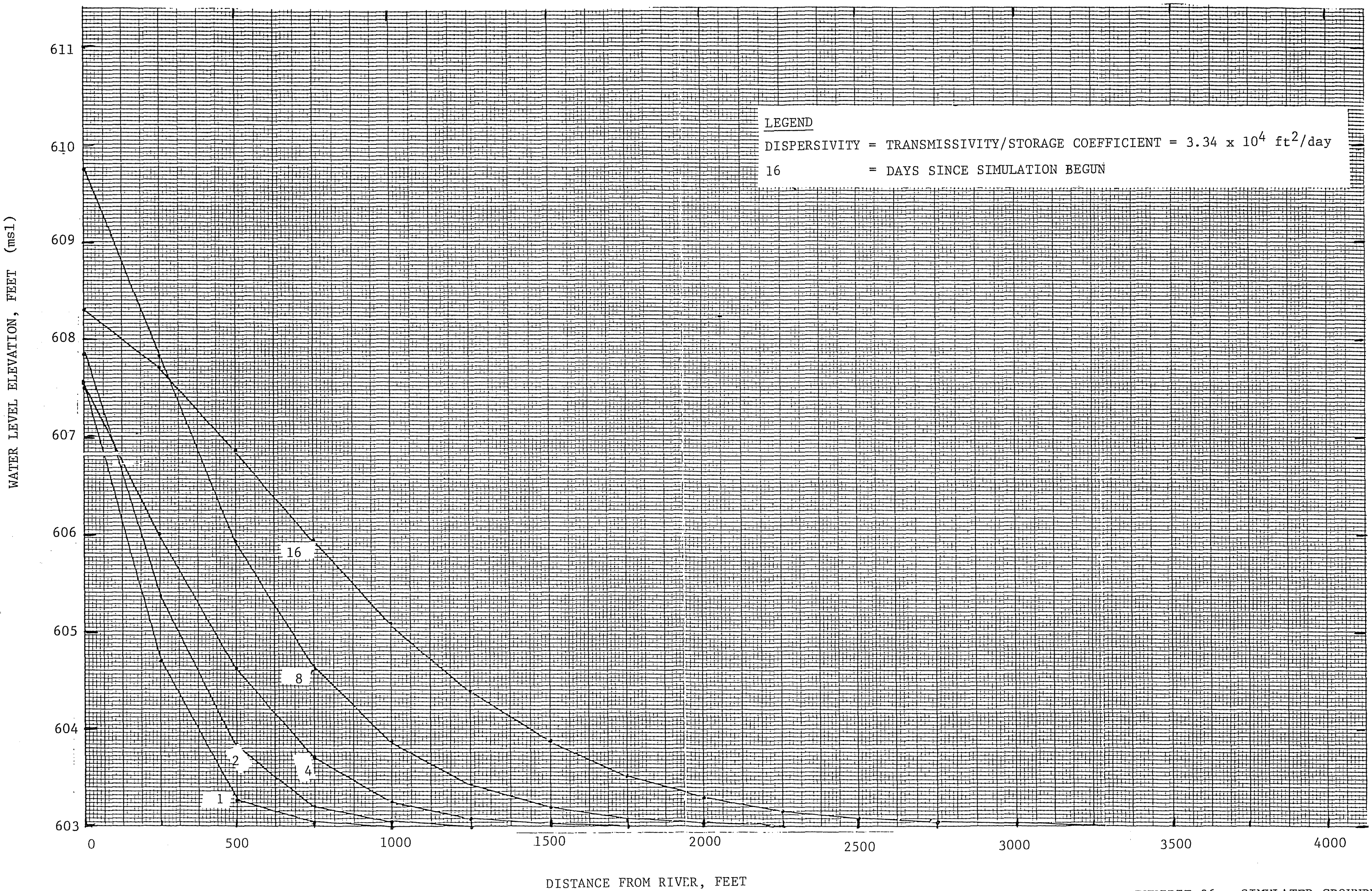

EXHIBIT 36. SIMULATED GROUNDWATER LEVELS VS. DISTANCE FROM RIVER, STORAGE COEFFICIENT= 0.2

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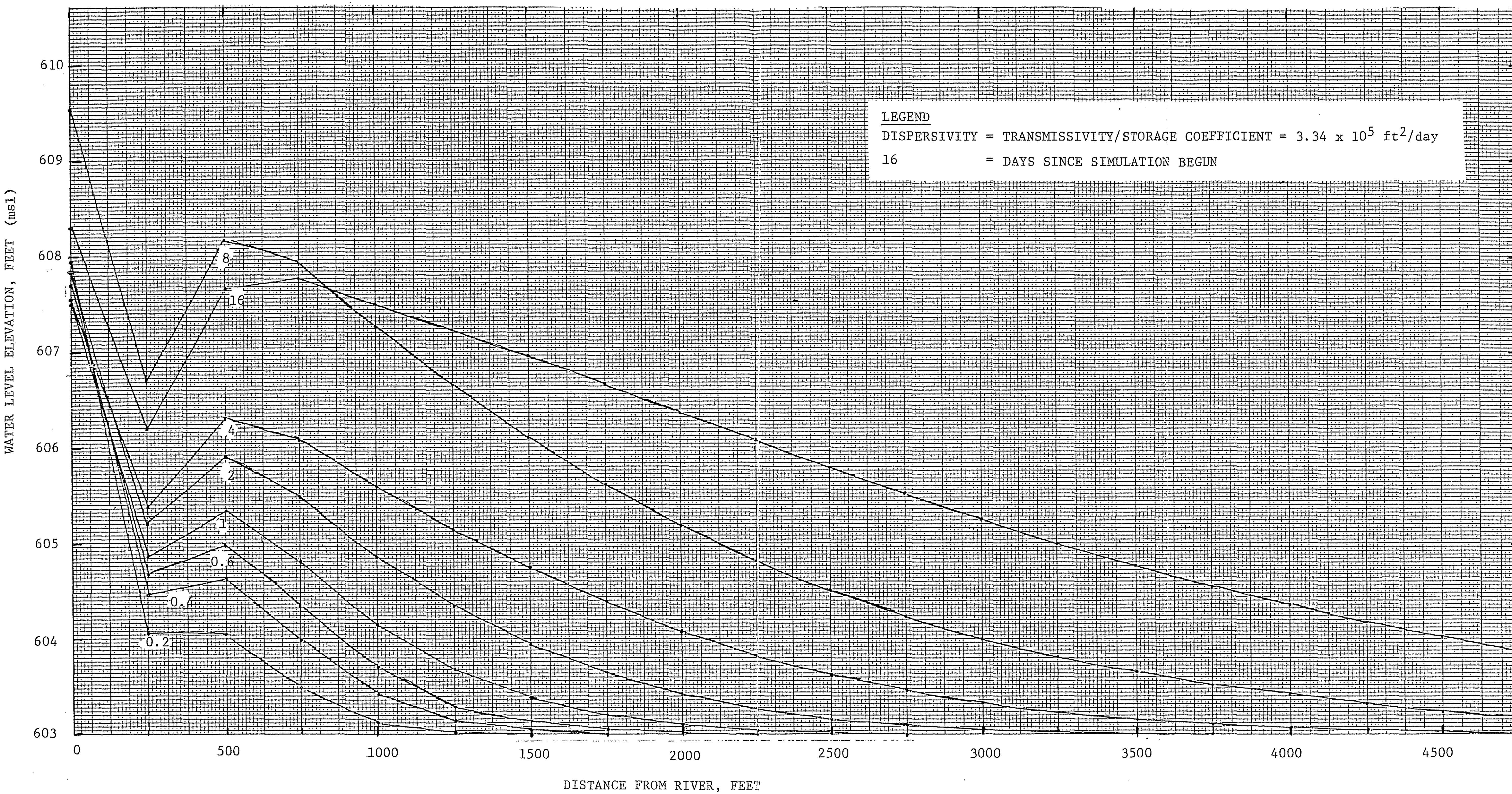

EXHIBIT 37. SIMULATED GROUNDWATER LEVELS VS. DISTANCE FROM RIVER, STORAGE COEFFICIENT = 0.02

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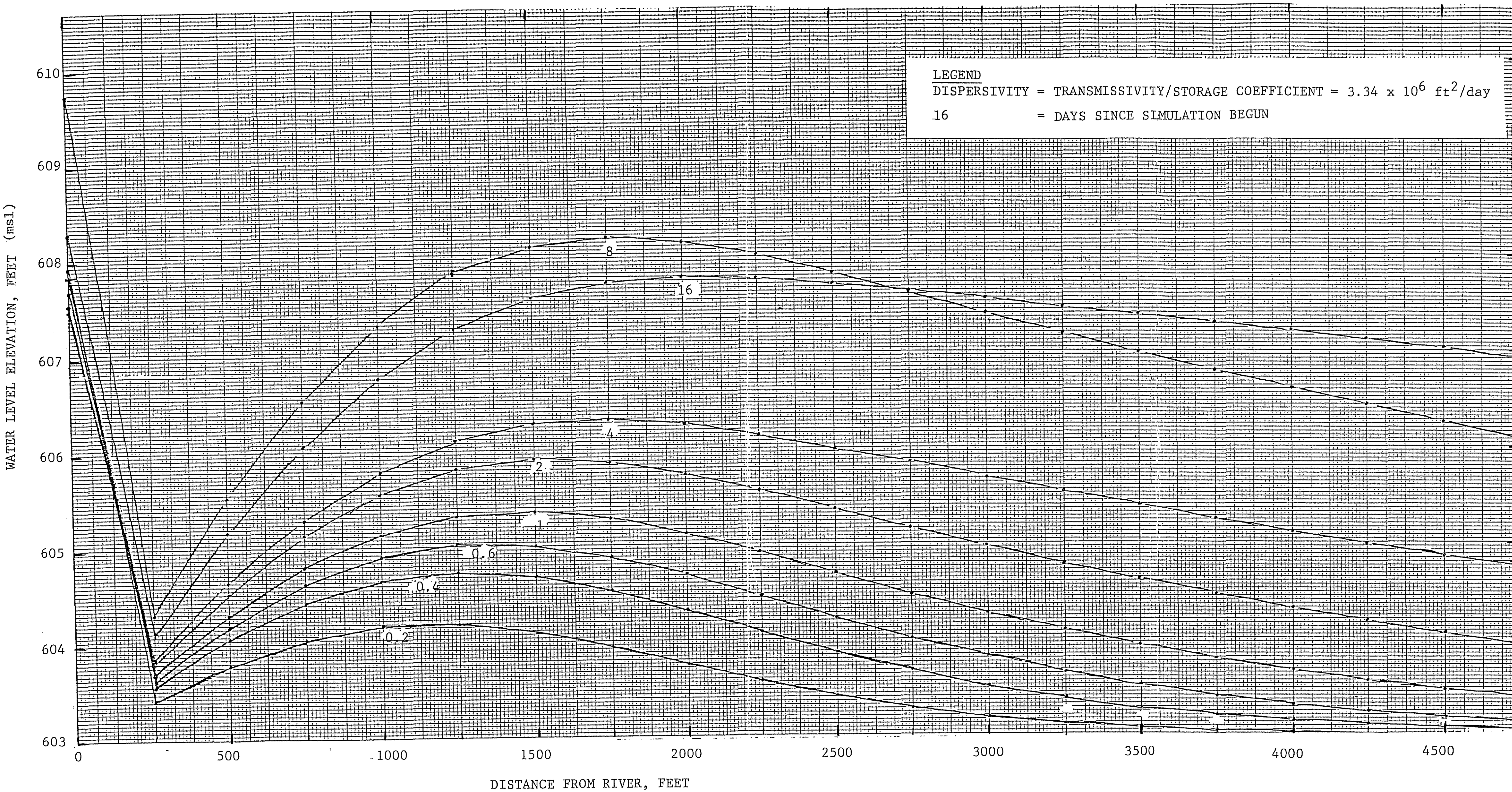

EXHIBIT 38. SIMULATED GROUNDWATER LEVELS VS. DISTANCE FROM RIVER, STORAGE COEFFICIENT = 0.002

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