SUS 257

SUSITNA HYDROELECTRIC PROJECT

SLOUGH GEOHYDROLOGY STUDIES

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1.0 INTRODUCTION

This report provides results of a study begun in September 1983 into 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 investigations into hydraulic and thermal relationships 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 on existing data collected during 1982 and 1983 by R&M Consultants and the ADF&G SuHydro Aquatic Studies Group. Those data have been used in a variety of statistical and other mathematical analyses in an attempt to identify significant interrelationships between mainstem and alough hydrologic conditions. No new data have been generated during this study, other than observations made during field reconnaissance trips and information gleaned from published reports.

2.0 METHODOLOGY

2.1 Data Compilation and Review

A variety of surface water, groundwater, and water quality data have been compiled from sources such as R&M Consultants, ADF&G, U.S. Geological Survey, and published and unpublished reports. The types of data which are 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 near slough 8 and sixteen wells 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 - occasional 1982 and 1983 records from 33 stations within and 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 - occasional summer 1983 readings from 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.

2.2 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 influence of groundwater discharge on slough conditions was more apparent.

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, servicing of the stage recorder at Deadman Creek was observed. The lower reaches of slough 9 were later toured on foot. Seepage meter measurements were observed at slough 11, and side slough 10 was visited briefly during the return to Talkeetna by boat.

2.3 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 include the Harza-Ebasco Joint Venture, 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.

2.4 Data Analyses

2.4.1 Aquifer Properties

Results of aquifer tests and specific capacity data in the Talkeetna area have been obtained from USGS files. These data have been subjected to standard hydrologic analyses for estimation of aquifer properties for the alluvial materials at that site. The resulting properties should be similar to those of the valley-fill materials further upstream, in the vicinity of the side sloughs.

Datapod hydrographs have been provided for mainstem stage and groundwater levels in wells at slough 9. Attempts have been made to interpret these data by applying published (8)[1/] techniques for estimating aquifer properties based on groundwater variations in response to stream stage variations.

2.4.2 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.

1/ Refers to the numbers in "References" at the end of the text.2.4.3

2.4.3 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.

2.5 Mathematical Modeling

2.5.1 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.

2.5.2 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, 6).

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 (6). 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 (6) to the coupled thermal and groundwater flow solution developed by Acres American (1).

3.0 RESULTS

3.1 Hydrogeologic Setting

3.1.1 Regional Geology

The regional geologic setting of the Susitna River between Devil Canyon and Talkeetna has previously been described in several works (5, 7, 9), 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 (9),

> " 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 (10, 13) 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.

3.1.2 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.

Sloughs are generally found on the left descending bank, with mainstem flow generally, but not consistently, along the right descending bank. Slough areas are generally well vegetated, except within the channel of the slough itself. Slough areas are generally contiguous with the valley wall area, occasionally separated by a tributary stream. The photographs were inspected for evidence of uniformity in paleo-channel width, as might be inferred from terrace or valley wall position. 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 terrace (?) valley walls 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 abandoned channel 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.

Upwellings (groundwater discharge withing the sloughs) are occasionally, but not consistently, visible on the photographs. There is 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. There may be some suggestion of upwelling within the mainstem, as evidenced by spots of dark water apparent within the turbid mainstem flow.

3.1.3 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. While no attempt has been made to generate synthetic storm hydrographs for each slough, total precipitation on the drainage area of a particular slough over relatively long periods of time (several months) has been compared with slough discharge over the same time periods. This approach was based on the rather simplistic assumption that cumulative precipitation over relatively long periods will approximate the sum of surface runoff and groundwater infiltration within a basin. In this manner an estimate can be made of the proportion of slough discharge derived from localized sources, such as direct precipitation on the slough drainage area plus integrated groundwater recharge within the drainage area, relative to the amount of slough discharge derived from external sources such as localized groundwater transport from the mainstem, or more regional groundwater underflow within the river basin.

The results of these analyses suggested that only very small proportions (of the order of a few per cent) of slough discharge could be attributed to precipitation, either directly as runoff or indirectly as infiltration and subsequent groundwater discharge to the sloughs. It is recognized, however, that these calculations are no substitute for the more detailed generation of synthetic storm hydrographs which are being developed by others. Nonetheless, based on these preliminary estimates, subsequent analyses were based on the working hypothesis that most of the discharge from sloughs 8A, 9, and 11 was derived from sources such as direct discharge from the mainstem as a result of overtopping of berms, regional groundwater underflow within the Susitna River alluvium, or more localized (and probably relatively shallow) lateral flow from the river toward the sloughs.

3.1.4 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 a hypothesis that a large proportion of the slough discharge may be derived from shallow lateral flow from the river, rather than regional groundwater underflow within the Susitna River valley-fill materials.. could tracer study be done

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 (9, 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., Fig. 1), 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 Fig. 1) 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.

Since no 1982 discharge measurements were available for slough 8A, the calculated unit flows (i.e., discharge per length of slough bank) were compared with mainstem discharge at the Gold Creek gage for selected dates (Figs. 2, 3). As can be seen from Fig. 2, there is no obvious correlation between the discharge per unit bank length and the mainstem discharge. However, from Fig. 3 it appears that there might be a time-series correlation with a lag of several 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.

Using a similar approach, estimates of the total groundwater discharge to sloughs 9 and 9A were compared with measured discharge from slough 9. For June 23, 1982, when the mainstem discharge at Gold Creek was 25,000 cfs and the slough 9 berm was probably 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 observations, except that the approximate groundwater discharge toward slough 9 appears to be of the same order of magnitude as the observed discharge from the slough during conditions of low-flow on the mainstem.

3.2 Aquifer Properties

3.2.1 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. 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-logarithimic and full-logarithmic paper, and standard analyses were conducted (11, 12). The Jacob straight-line analysis of the semi-logarithmic data plot (Fig. 4) 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 adjacent 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. 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.

3.2.2 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, and have been obtained from U.S.G.S. files. Utilizing graphs presented by Walton (11, 12), the estimated transmissivity determined from these data ranges from 2,400 to 14,000 gpd/ft assuming water table conditions, and from 4,400 to 27,000 gpd/ft assuming artesian conditions. The results are summarized on Table 1.

Of the six wells for which specific capacity data are available, well depths were reported for only three. All three wells were only 17 feet deep, and thus would be expected to exhibit water-table conditions in this environment. By dividing the estimated transmissivity by the original saturated thickness in each of these three wells, hydraulic conductivity values ranging from 240 to 1300 gpd/ft^2 are obtained, with a mean of 710 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.

3.2.3 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 were analyzed according to methods described by Pinder et al. (8). However, the field data could not be matched to the theoretical type curves generated by the methods of Pinder et al. (8), 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 (Fig. 5). 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 (Fig. 5).

It appears that the hydrologic conditions affecting the wells near slough 9 are considerably different than those assumed in the theory. For example, 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 and possibly by groundwater underflow originating far upriver from the slough or from the bedrock areas southeast of the slough. 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. 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.

3.3 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 beses in standard statistical techniques, confer a considerable degree of reliability on results of its application.

3.3.1 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 have been observed. In many important respects, the three sloughs for which most data are available behave differently.

The general relationship between slough and mainstem discharge is illustrated by Figure 6, which shows discharge versus time for the mainstem at Gold Creek (provisional 1983 USGS data) and for sloughs 8A, 9, and 11 (provisional 1983 R&M Consultants data). 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. 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 Figure 6, so slough 9 actually acts as a side channel to the mainstem during much of this period. Slough 11 exhibits very little variation in discharge at the scale plotted on Figure 6. Nonetheless, the slough 9 discharge also appears to reflect the relatively high mainstem flows observed in early June, and the steadily declining mainstem flow observed in mid-September.

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. Furthermore, a plot of slough 11 discharge versus mainstem discharge exhibits a linear form with a positive slope (Fig. 7). 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, and thus are probably biased since slough 9 was reportedly overtopped during much of the summer of 1983.

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 of this slough is extremely small, so that slough discharge is less likely to include surface runoff as a complicating factor. 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.

It should also be noted that whereas a plot of slough 8A discharge versus mainstem discharge shows considerable scatter and can not be readily represented by a single functional form, some of the data can be segmented into different time periods during each of which a fairly strong linear relationship between slough discharge and mainstem discharge can be observed (Fig. 8). The time periods illustrated in Figure 8 are distinguishable by the fact that each of them is either a period of generally rising river stage, or generally falling river stage. Furthermore, linear fits to the data during different periods of falling river stage (August 14-20 and September 2-17) generally have about the same slope, while fits to the data during different periods of falling stage have substantially different slopes (during the period August 20-25, while the river stage was rising, the slough discharge was actually decreasing). This information suggests that, at least at slough 8A, phenomena such as bank storage may be significant in controlling slough discharge. Since similar relationships have not been observed in the data from sloughs 9 or 11, this phenomenon may be localized to the vicinity of slough 8A.

3.3.2 Seepage Meter Data

The seepage meter data are generally consistent with the slough discharge correlations discussed above. Figure 9 shows plots of seepage meter data versus both mainstem and slough discharge data. The seepage rates at meters 8-1, 8-2, 9-1, and 9-3 are generally positively correlated with either mainstem or slough discharge, although the data are rather widely scattered about the linear regression fit to the data (Figs. 9a - 9c). However, seepage rates at meter 9-2 seem to be uncorrelated with either mainstem or slough discharge (Fig. 9b). At slough 11, the seepage rates at both meters 11-1 and 11-2 are very well correlated with both mainstem and slough discharge. This tends to confirm the previous observations that discharge at slough 11 is strongly correlated with mainstem discharge, and there is a good likelihood that upwelling at slough 11 is derived rather directly from mainstem recharge to the local groundwater aquifer.

Seepage meter data at slough 21 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, rather than groundwater underflow from the river.

3.3.3 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. In some cases, ADF&G was gracious enough to provide data which had not even been fully reduced, in order to expedite the present study. Thus 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 (Fig. 10). The intragravel data 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 (Fig. 10b). 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 (Fig. 10b). 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 in the 1983 record, the high temperatures observed in the surface water at the middle of the slough can probably be attributed to solar heating, rather than groundwater inflow or 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.

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 (Fig. 11). Both mainstem probes, as well as the surface water probe within the slough, show essentially the same behavior: winter temperatures are near zero, with the intragravel temperature about a degree higher than the surface water temperature at the mainstem during late September and October of 1983; temperatures at all three points begin to increase in mid-May and reach maximums of about 13° in late June, and persisting through July; temperatures then fall to near zero by late September. 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 (Fig. 11). The groundwater data show considerably more variation than the slough intragravel data. At borehole 9-1A, which is nearest to the river, temperatures reached a low of about 2.5 ° in late February, and then rose to over 5° in early September. At borehole 9-5, near slough 9B, temperatures fell from 4° in early January to 2.5° during April, and then rose to about 5.5° in early October before again falling. At borehole 9-3, temperatures were relatively stable, varying between 3.5° and 4.5°. 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 (Fig. 11).

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.

At slough 11, data are available for surface water and intragravel measuring points within the slough, and surface water measuring points on the mainstem (Fig. 12). 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 (Fig. 13). 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. 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. Except at the mouth of slough 21, intragravel temperatures were essentially the same as surface water temperatures at comparable points, suggesting that the intragravel water may result from downwelling of surface water rather than upwelling of cooler groundwater.

3.4 Analytical Models

Limited mathematical modeling of groundwater levels and temperatures has been performed during this study. 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. No attempt was made to actually simulate groundwater discharge to the sloughs, or the temperature of such discharge. To this end, some simple one-dimensional analytical models were applied.

3.4.1 Groundwater Level Variations

As described by Hall and Moench (6), 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 (6) 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, is given by (6)

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

and 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.

Figure 14 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 (R&M Consultants provisional data). 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 Figure 14. It is interesting to note that the observed groundwater levels are most closely matched by simulated curves for artesian conditions, rathet than water table conditions (i.e., for a storage coefficient of 0.0002 rather than 0.2). 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, well logs in the vicinity of slough 9 (9) would suggest 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.

Figures 15a through 15d 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, Figure 15d 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, Figure 15a 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.

3.4.2 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 (6), 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. 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 (6). P(x,t) is essentially the solution given by Acres American (1),

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

where $\bar{T}(x,t)$ 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.

4.0 CONCEPTUAL SYSTEM MODEL

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 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.

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 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.

It is doubtful that additional studies within project constraints can improve significantly on the current status of knowledge regarding the sloughs. However, 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 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 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.

5.0 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 a model of each individual slough in order to make detailed predictions of the effects on the sloughs of changes in mainstem conditions. 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 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. However, any such relationship can not be quantified based on available data.

Some sloughs, such as slough 9 during the summer of 1983, will be 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, 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 very extensive 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.

Temperatures of groundwater discharge to the sloughs appears to be reasonably approximated by the mean annual 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 are 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. Again, it is not possible with present information to quantify such effects.

6.0 SUMMARY

This study provides a review of much available hydraulic and thermal data regarding the discharge and temperature of side sloughs tributary to the Susitna River between Devil Canyon and Talkeetna. This review of the data has served to illustrate the complexity of hydraulic conditions at the sloughs. It has not been possible to formulate a single conceptual model which can serve to describe each individual slough. On the contrary, each of the sloughs studied in detail differs significantly from the other sloughs in one or more important respect. Because of these complexities, it is not possible to quantitatively predict the changes in slough discharge or temperatures which might result from changes in mainstem conditions as a result of project operation.

The discharge from some individual sloughs (such as slough 11) can probably be correlated fairly well with mainstem discharge, so that projections could be made of the changes in slough discharge which would result from changes in mainstem discharge. However, the discharge from most sloughs will probably be influenced by diversions from the mainstem as a result of overtopping, overland runoff and tributary discharge, and other factors which will preclude detailed projections of discharge for each slough in the study reach.

The temperature of groundwater discharge to the sloughs does appear to remain relatively constant at a temperature approximately equal to the mean annual river temperature. However, without knowing the proportion of discharge from an individual slough which can be attributed to such groundwater discharge, it is not possible to project the time-variation of heat which is available for salmon incubation at a particular slough.

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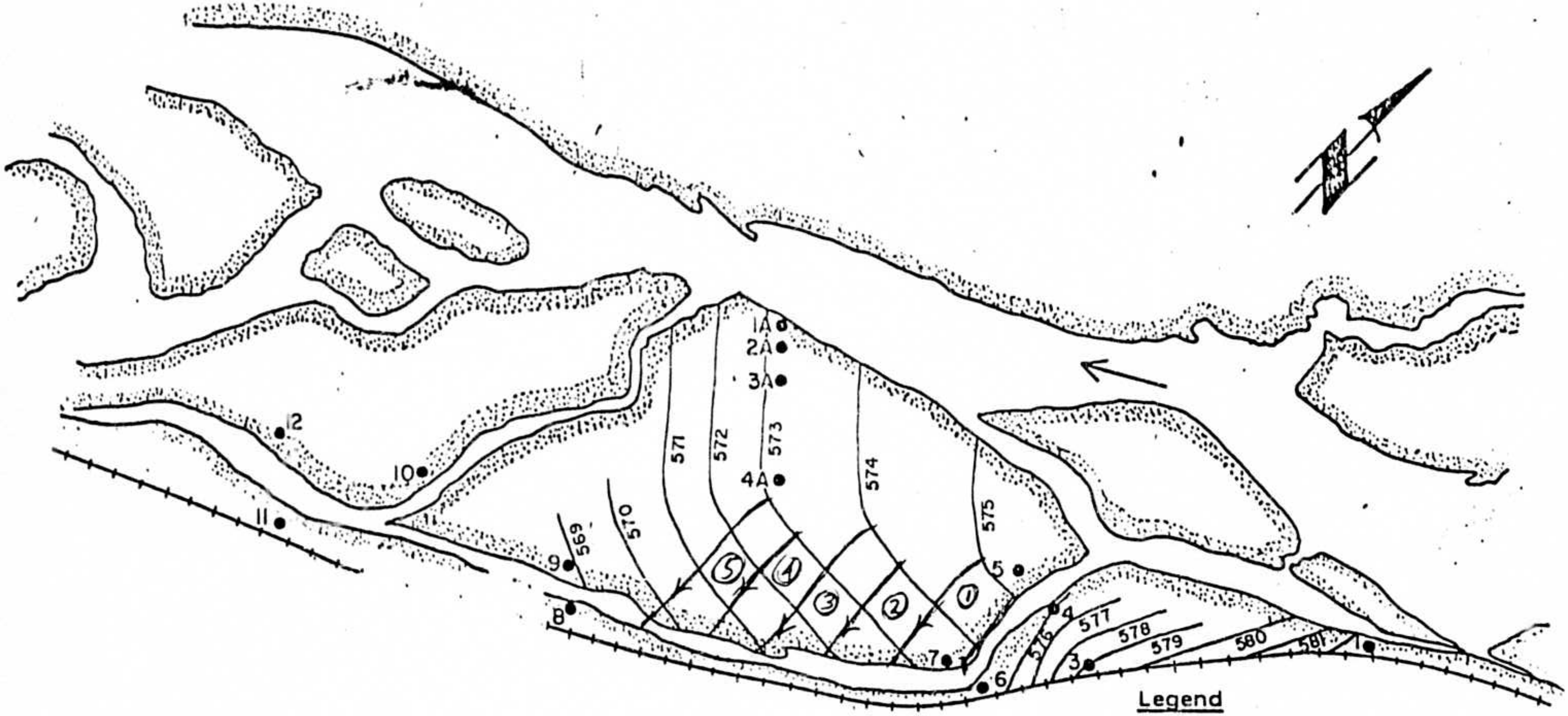
SPECIFIC CAPACITY

Well No.	Reported Spec. Cap. (gpm/ft)	Well Depth	Length of Pumping Period	Table Values	Inferred Transmissivity (gpd/ft)[1] Artesian (S=.0001)	Inferred Transmissivity (gpd/ft)[1] Water Table (S=0.2)
17[2]	6.0	17'	4 hrs.	(4 hr)	10,000	(5,060)
				(8 hr)	10,200	6,400
	6.76		16 hrs	(24)	14000	8000
18	2.65	17'	8 hrs.	(8 hrs)	5,000	2,600
19	2.14	17'	16 hrs.	(24 hrs)	4,400	2,400
10	11.5	?	2 hrs.	(8 hrs)	27,000	(14,000)
				(1 hr)	22,000	11,000
11 & 15	3.33	?	2 hrs.	(1 hr)	5,400	2,500
			AVERAGE (EXCLUDING VALUES IN ( ))			5,500 gpd/ft

(1) Based on Walton (11, 12)

(2) Two tests for well 17

Table 1. Transmissivity Estimates Based on Specific Capacity Data for Talkeetna Wells



Sketch map and groundwater contours from R+M Consultants (9)

Approx scale: 1" = 1000'

← inferred groundwater flow line

(3) flow tube

Legend

● observation well

"600" groundwater elevation

Date: 9-20-82

Q_{GC}: 24,000

Figure 1. Groundwater Contours and Flow Lines, Susitna River at Slough 8A

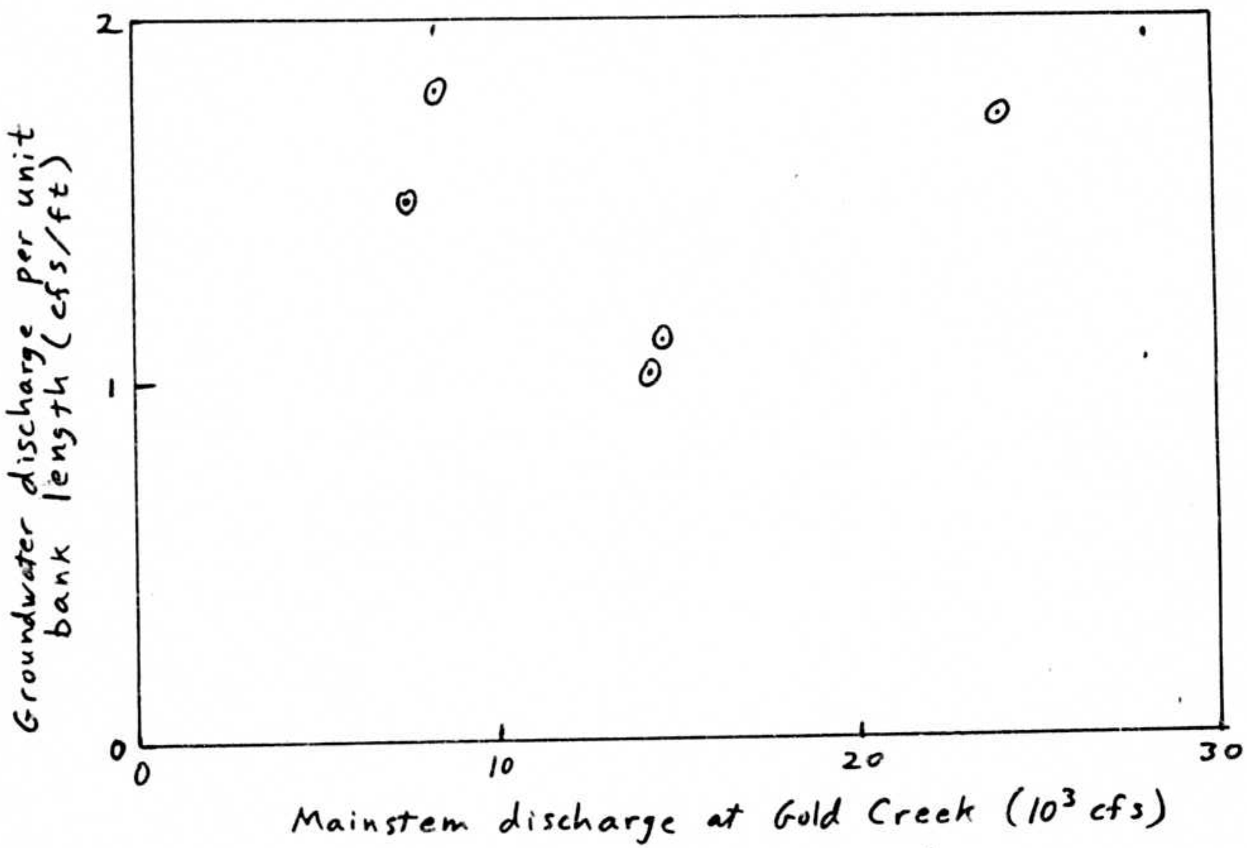


Figure 2. Groundwater Discharge vs. Mainstem Discharge, Slough 8A in 1982

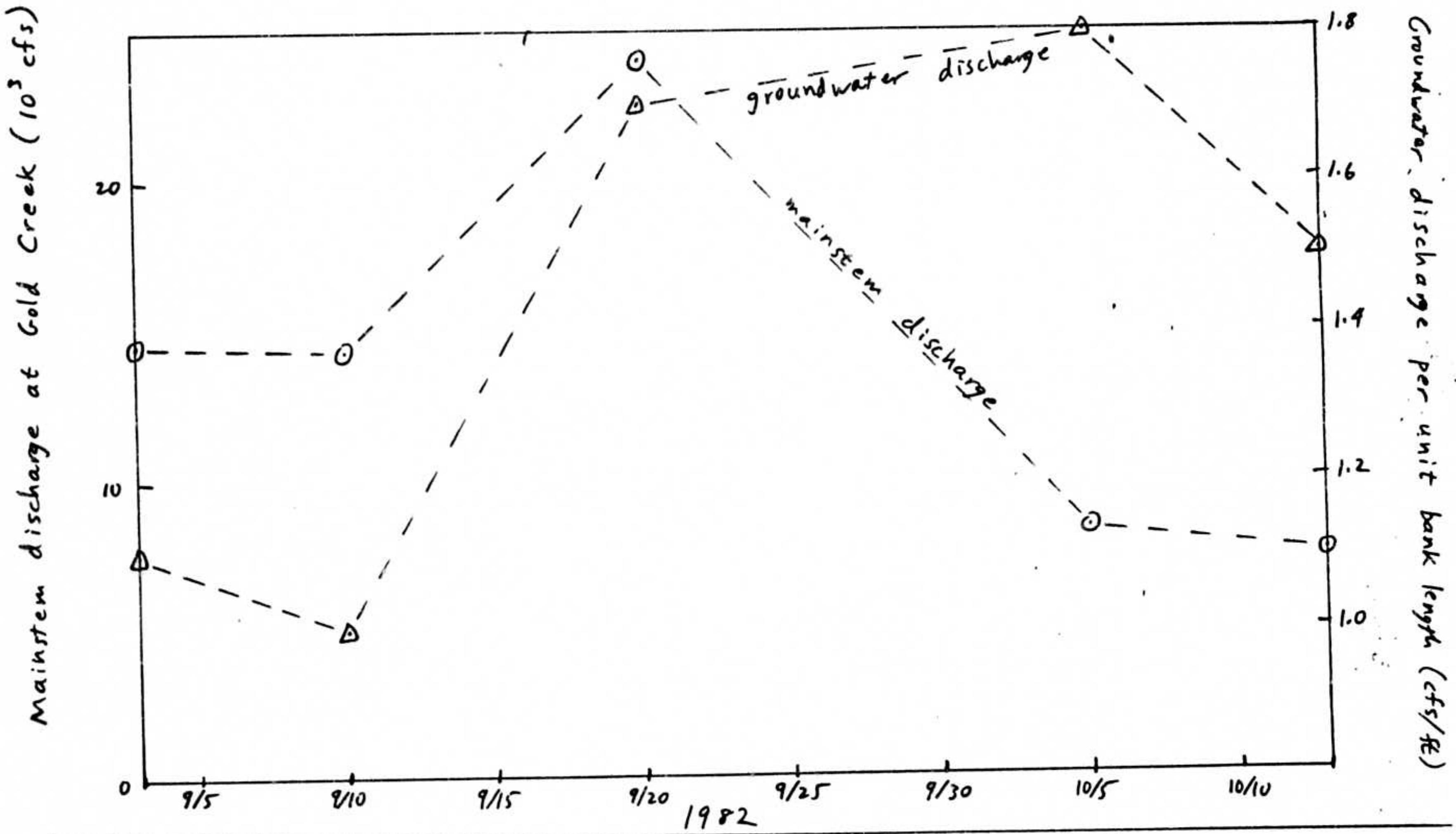


Figure 3. Groundwater Discharge and Mainstem Discharge vs. Time, Slough 8A in 1982

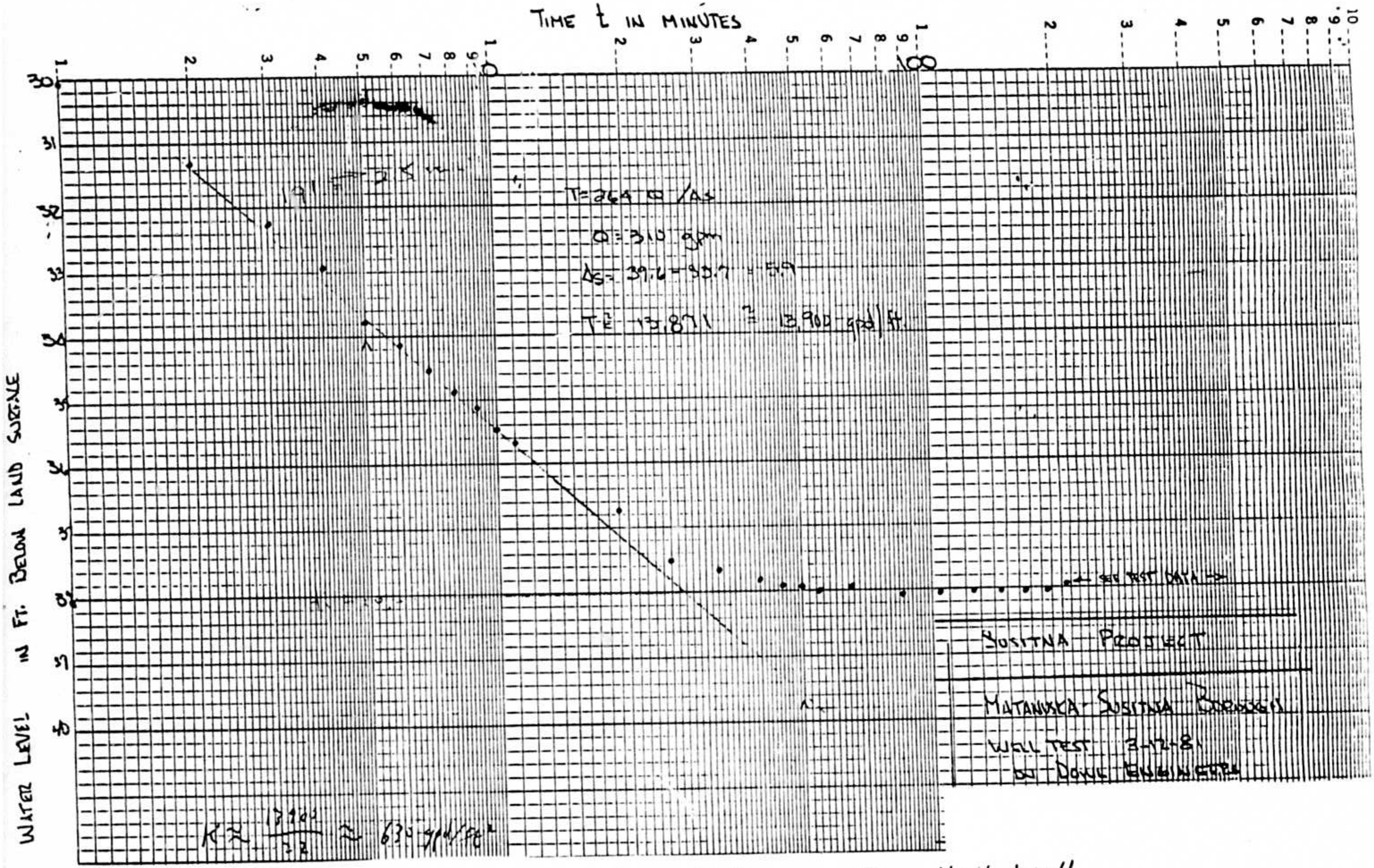
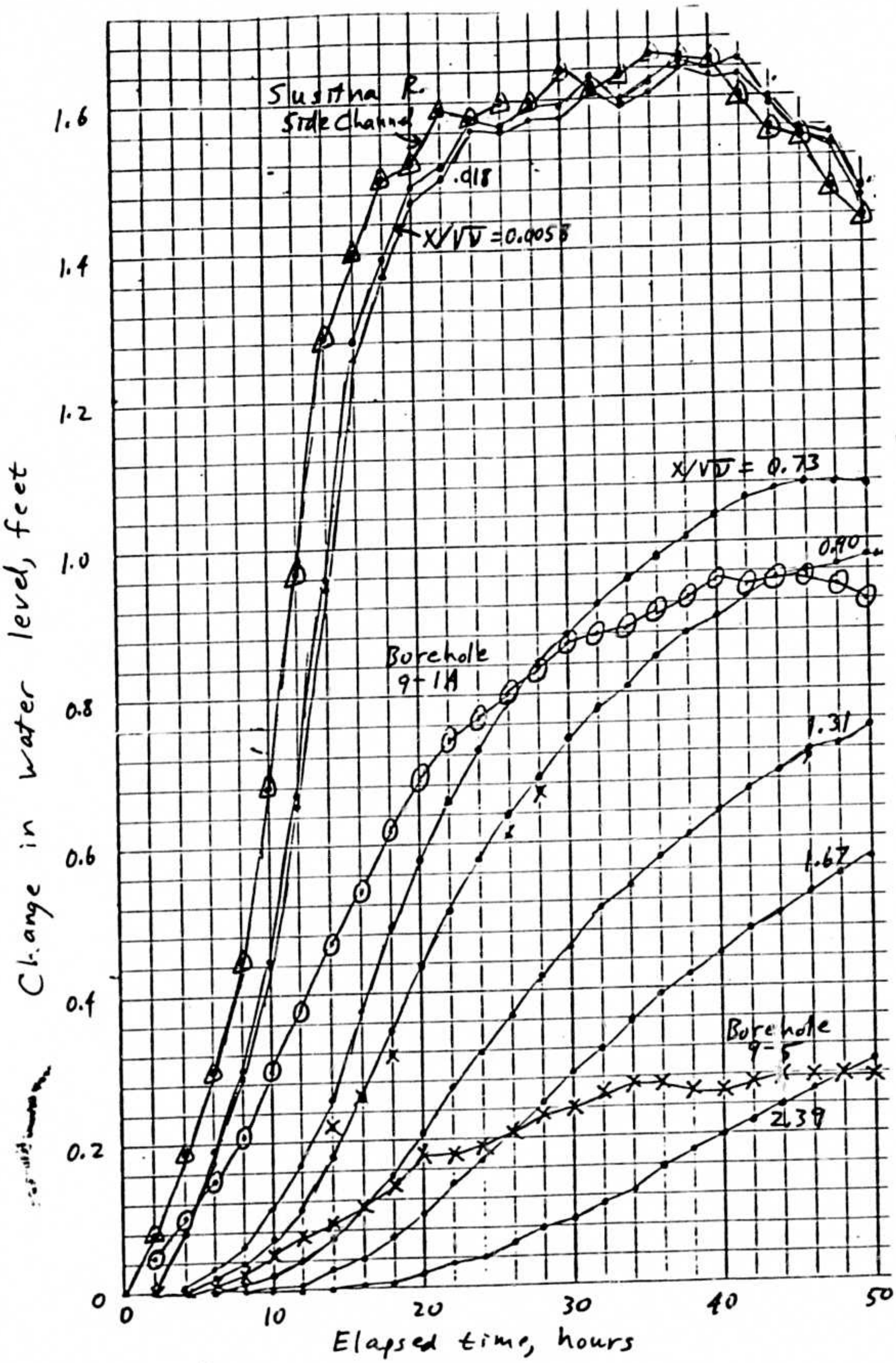


Figure 4. Aquifer Test Data, Talkeetna Fire Hall Well, March 1981 Pumping Test



X = distance from river bank

ν = aquifer diffusivity, ratio of transmissivity (T) to storativity (S)

Figure 5. Groundwater Level Variations in Response to River Stage Fluctuations

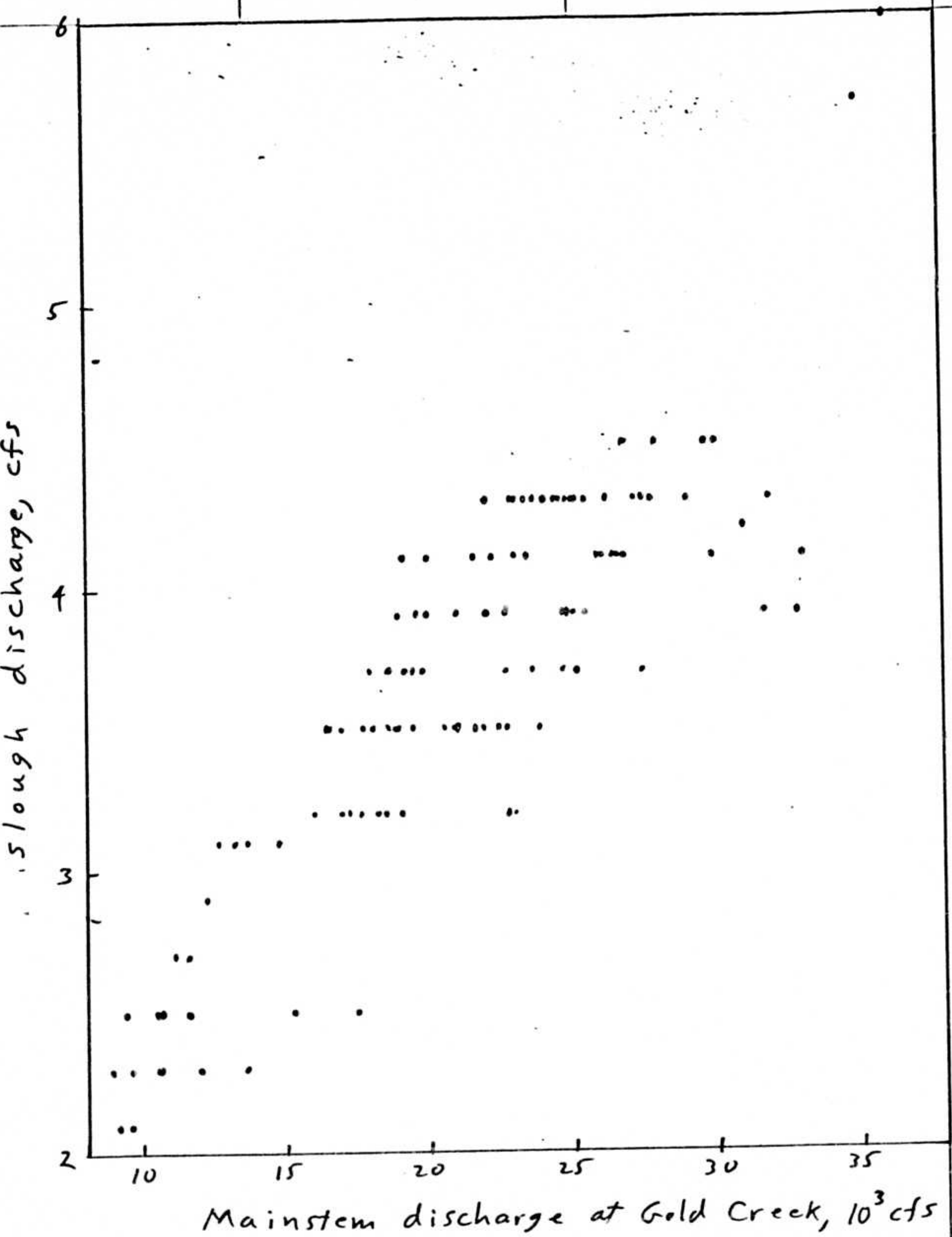


Figure 7. Slough 11 Discharge vs. Mainstem Discharge at Gold Creek

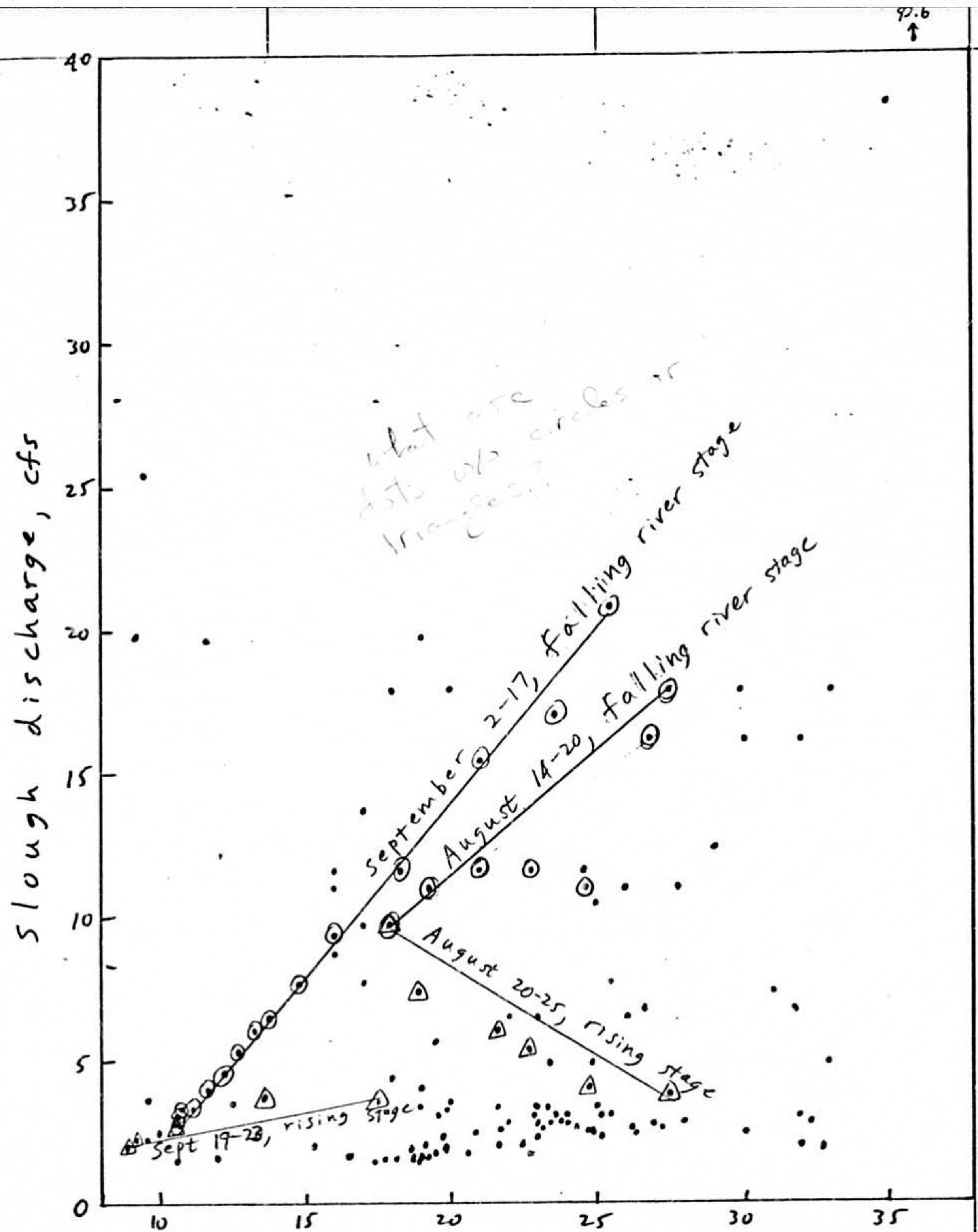


Figure 8. Slough 8A Discharge vs. Mainstem Discharge at Gold Creek

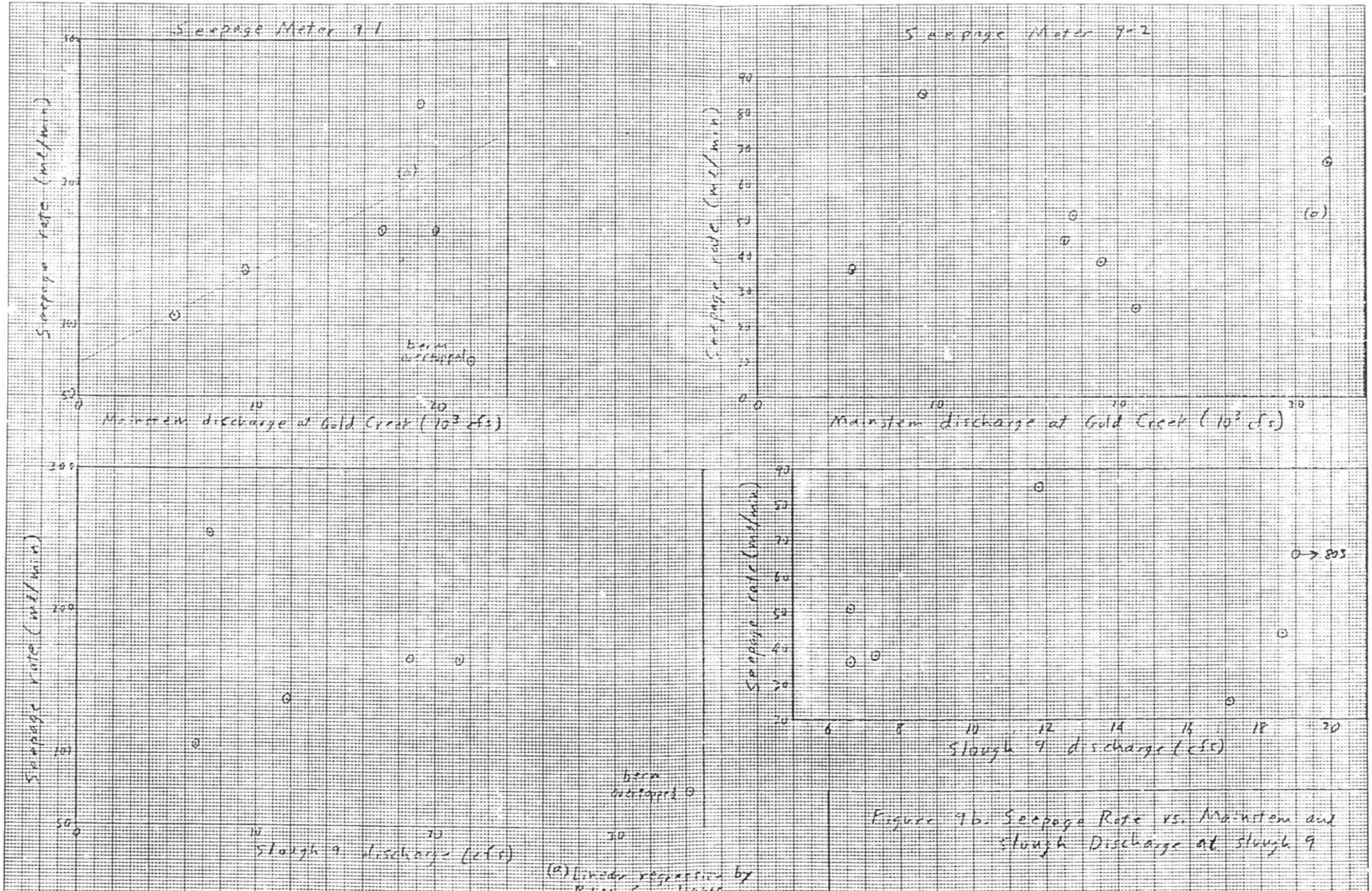
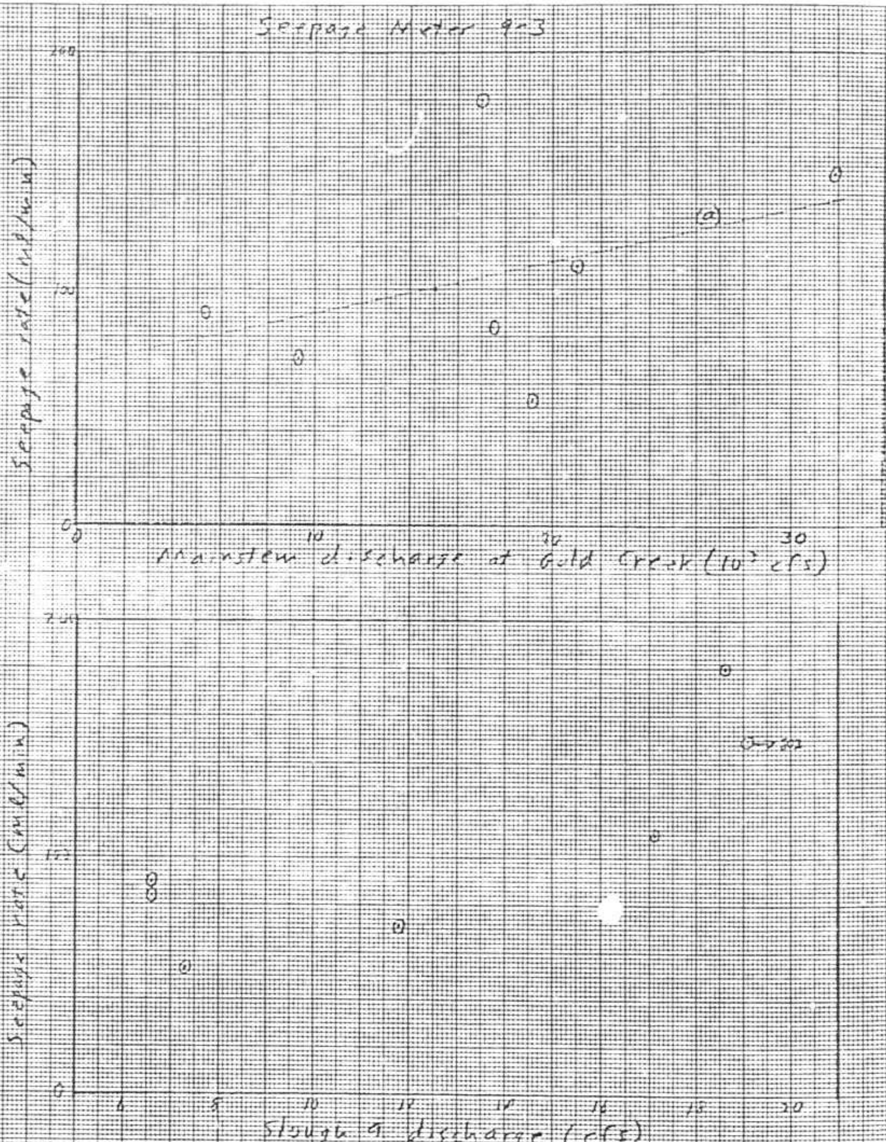


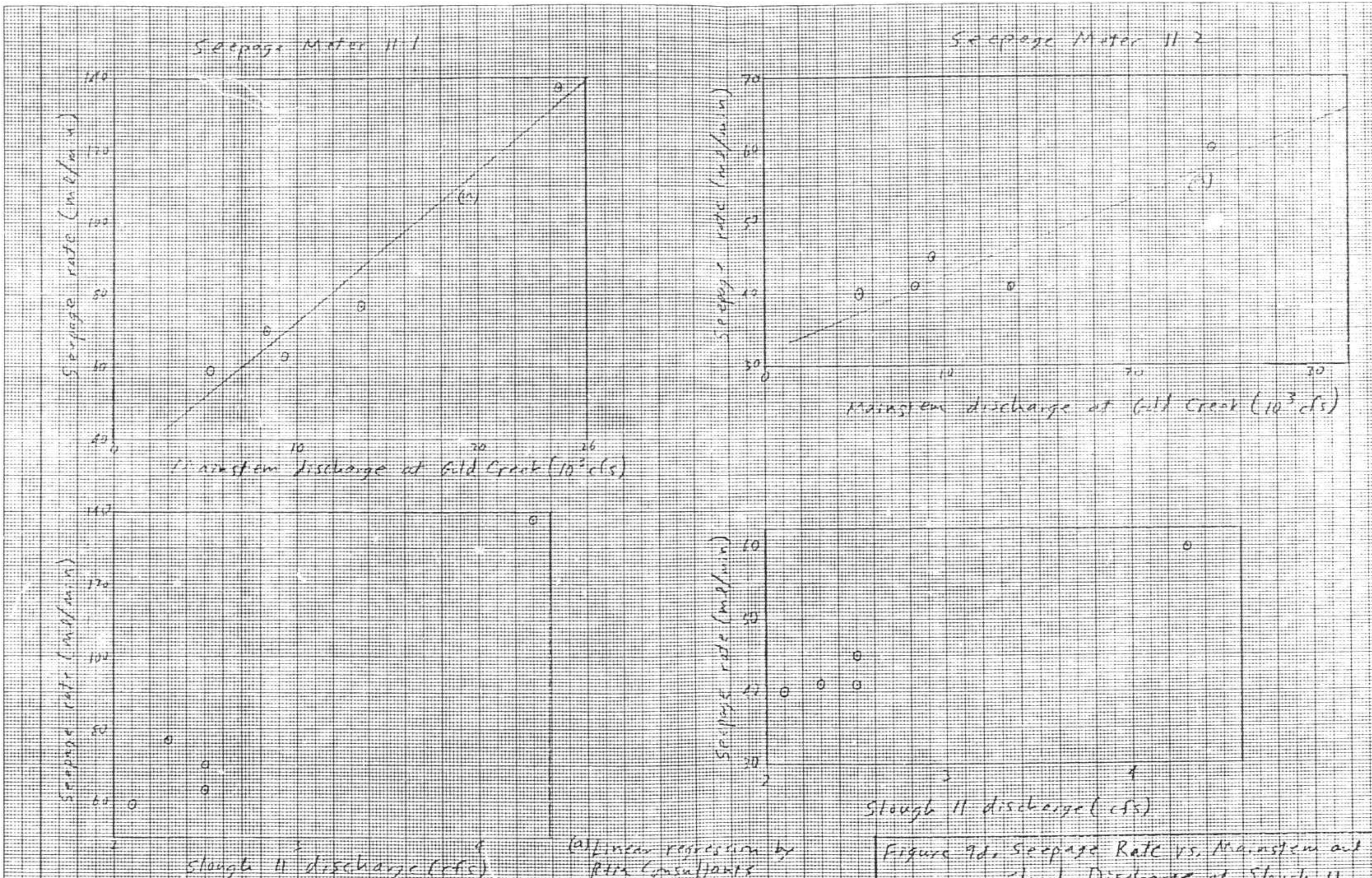
Figure 9b. Seepage Rate vs. Mainstem and Slough Discharge at Slough 9

(a) Linear regression by R&M Consultants



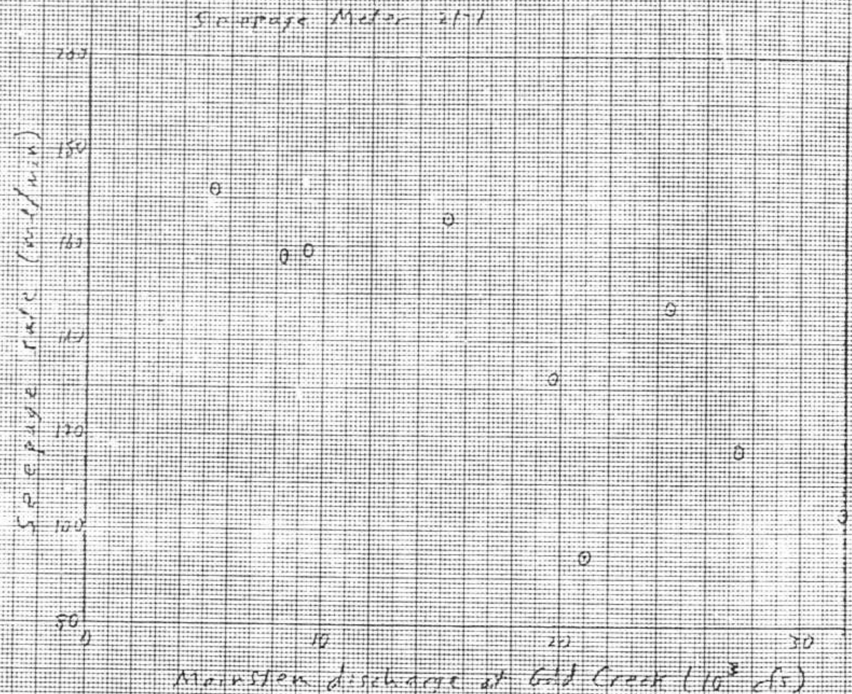
(a) Linear regression by R&M Consultants

Figure 9c. Seepage Rate vs. Mainstem and Slough Discharge at slough 9 meter 9-3



(a) Linear regression by R&M Consultants

Figure 9d. Seepage Rate vs. Mainstem and Slough Discharge at Slough 11



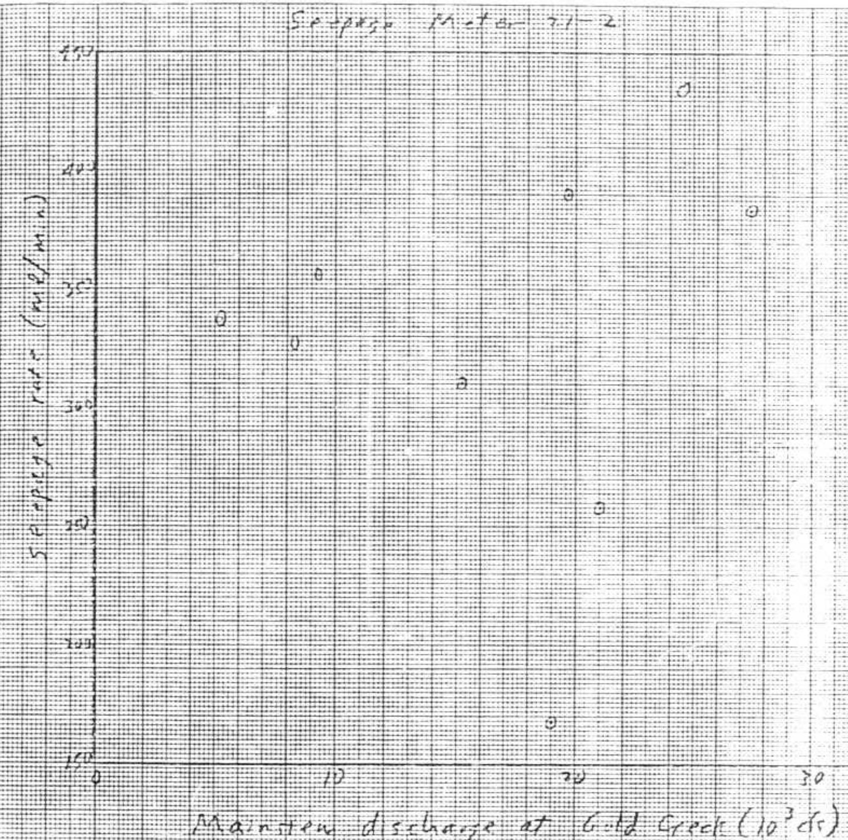


Figure 9e. Seepage Rate vs. Mainstem Discharge at Slough 21

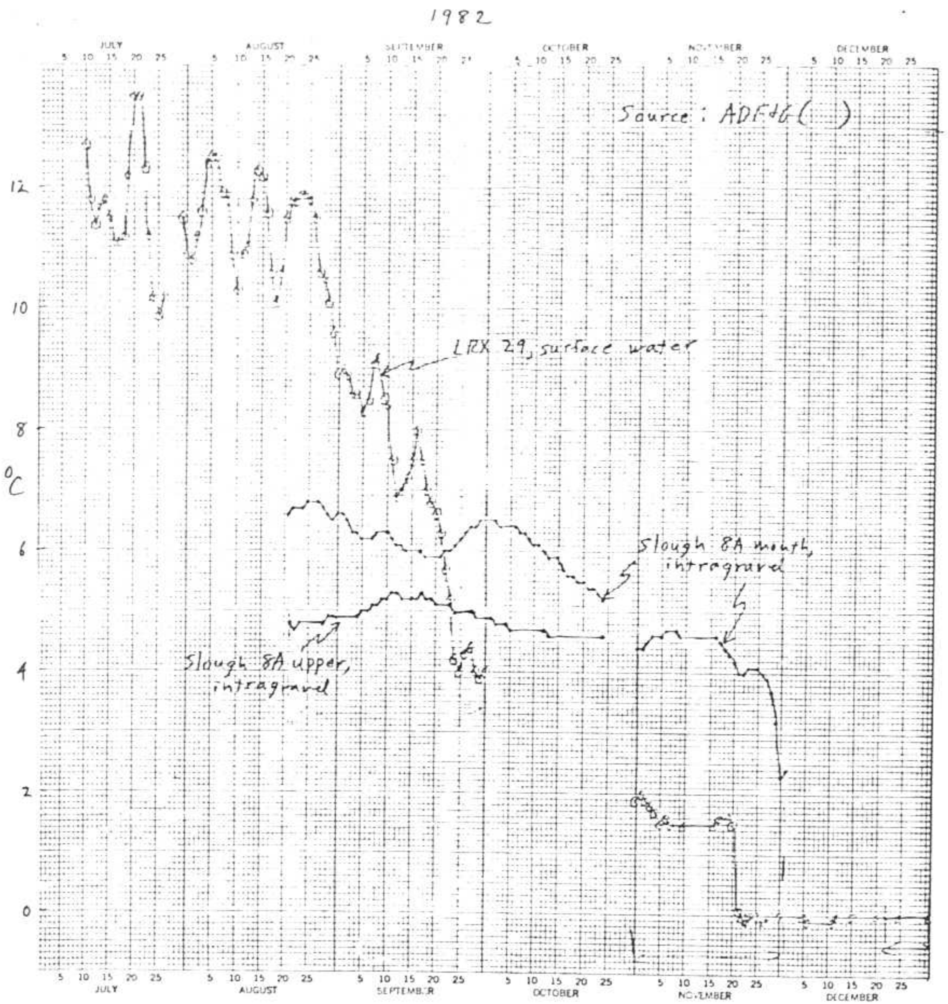
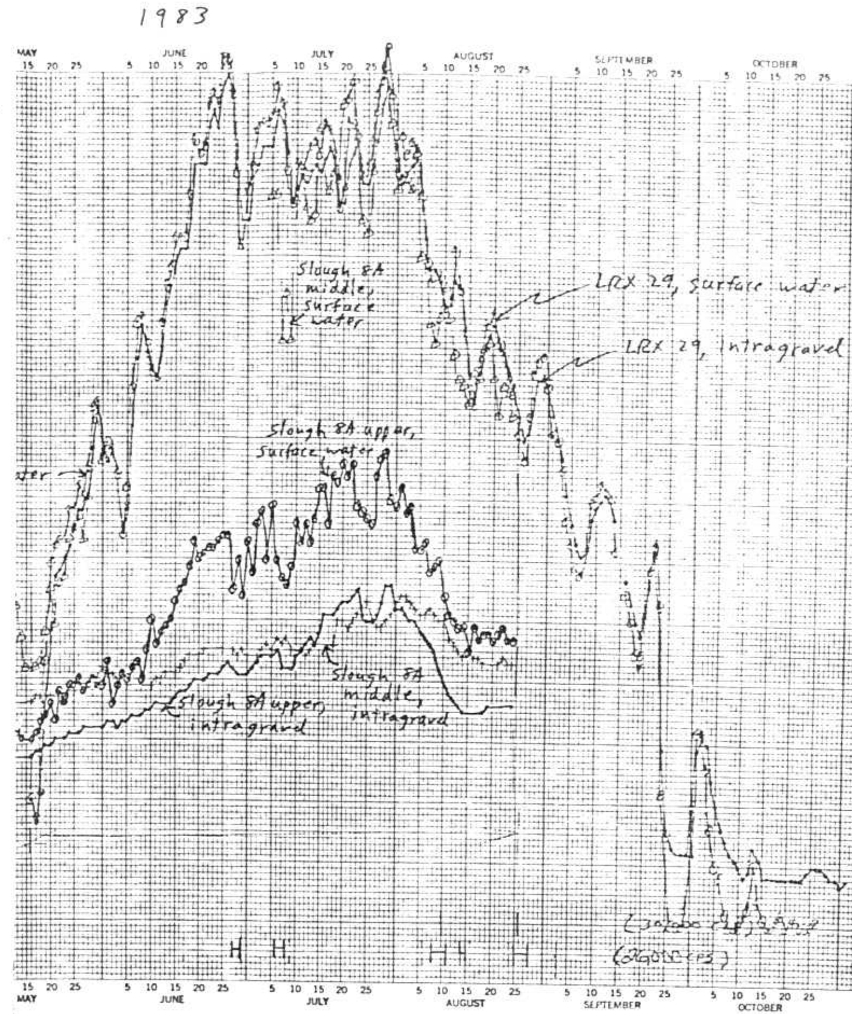
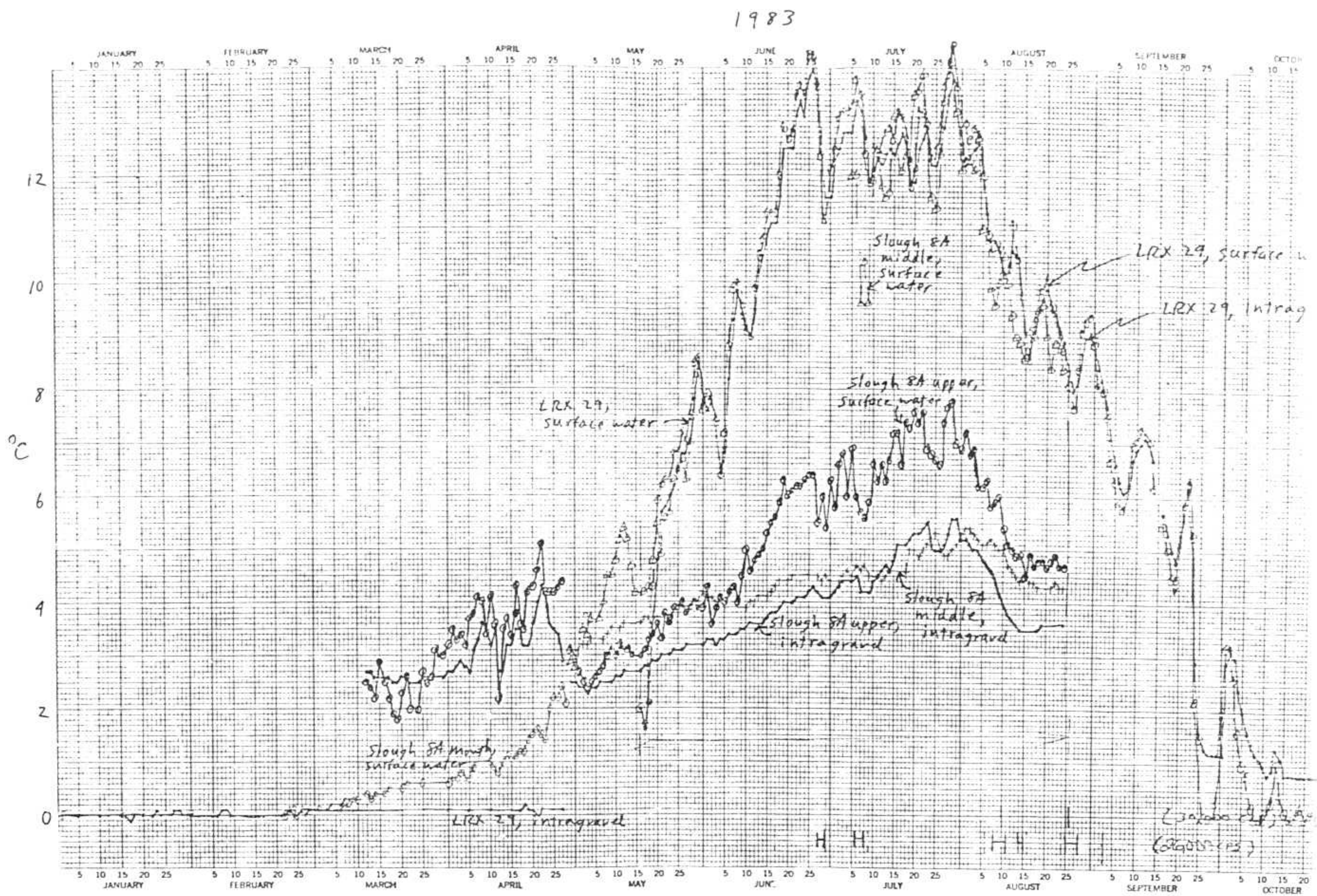


Figure 10a. Slough 8A Water Temperatures, 1982.



Data

Figure 10 b. Slough 8A Water Temperatures, 1983



Sources: ADF+G (3)
ADF+G Provisional 1983 Data

Figure 10b. Sloug
Tempe

1983

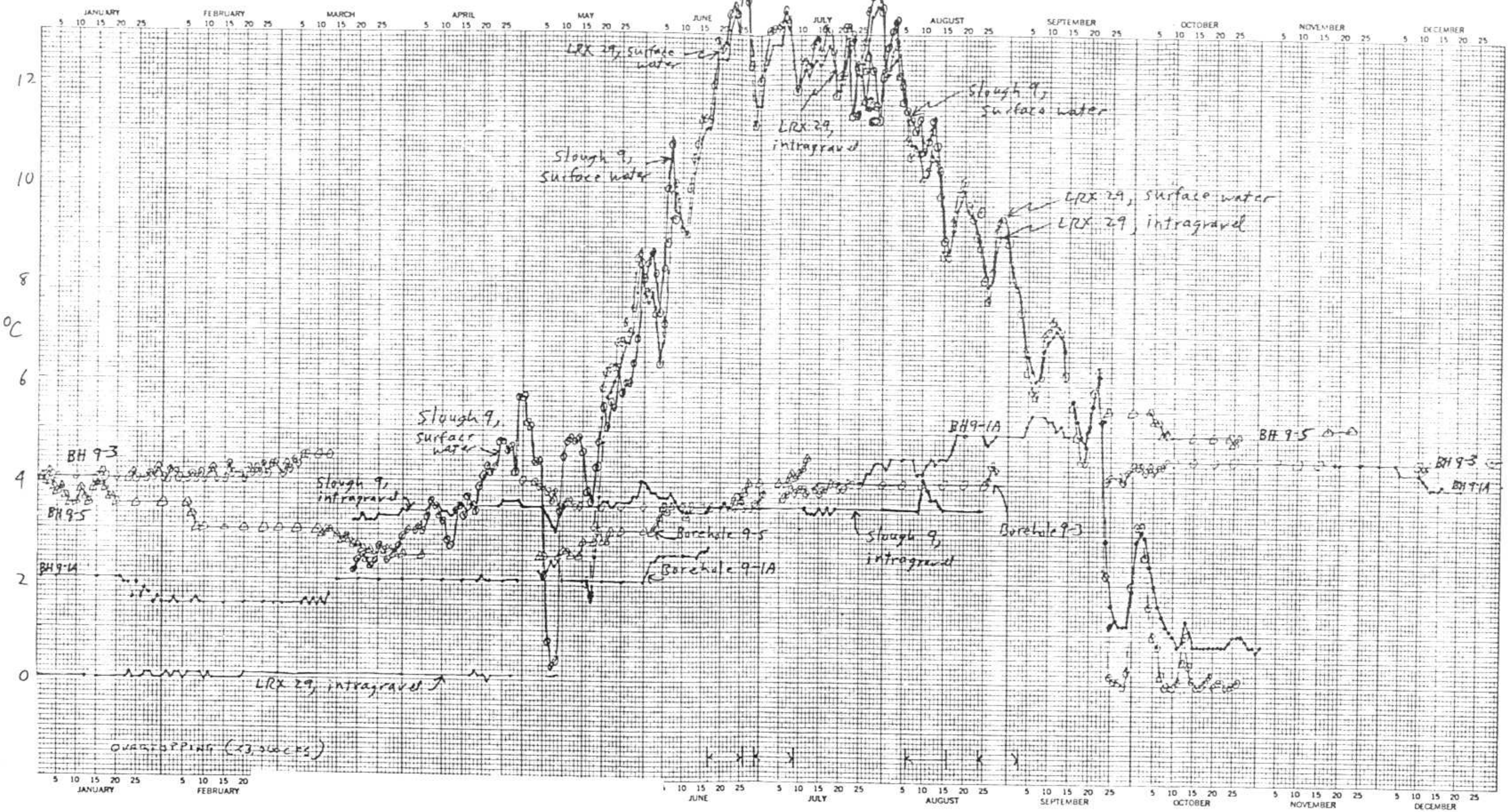
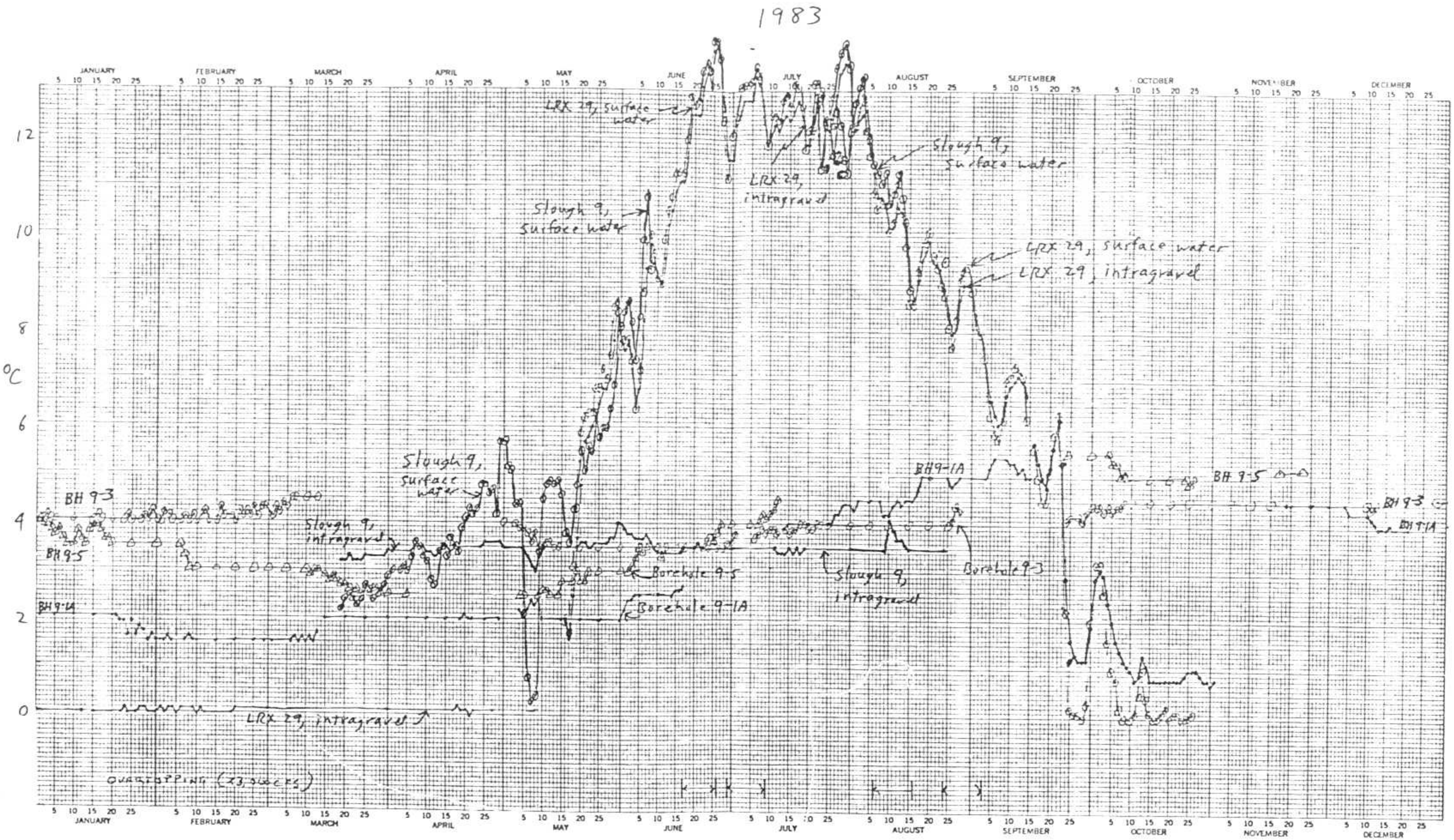


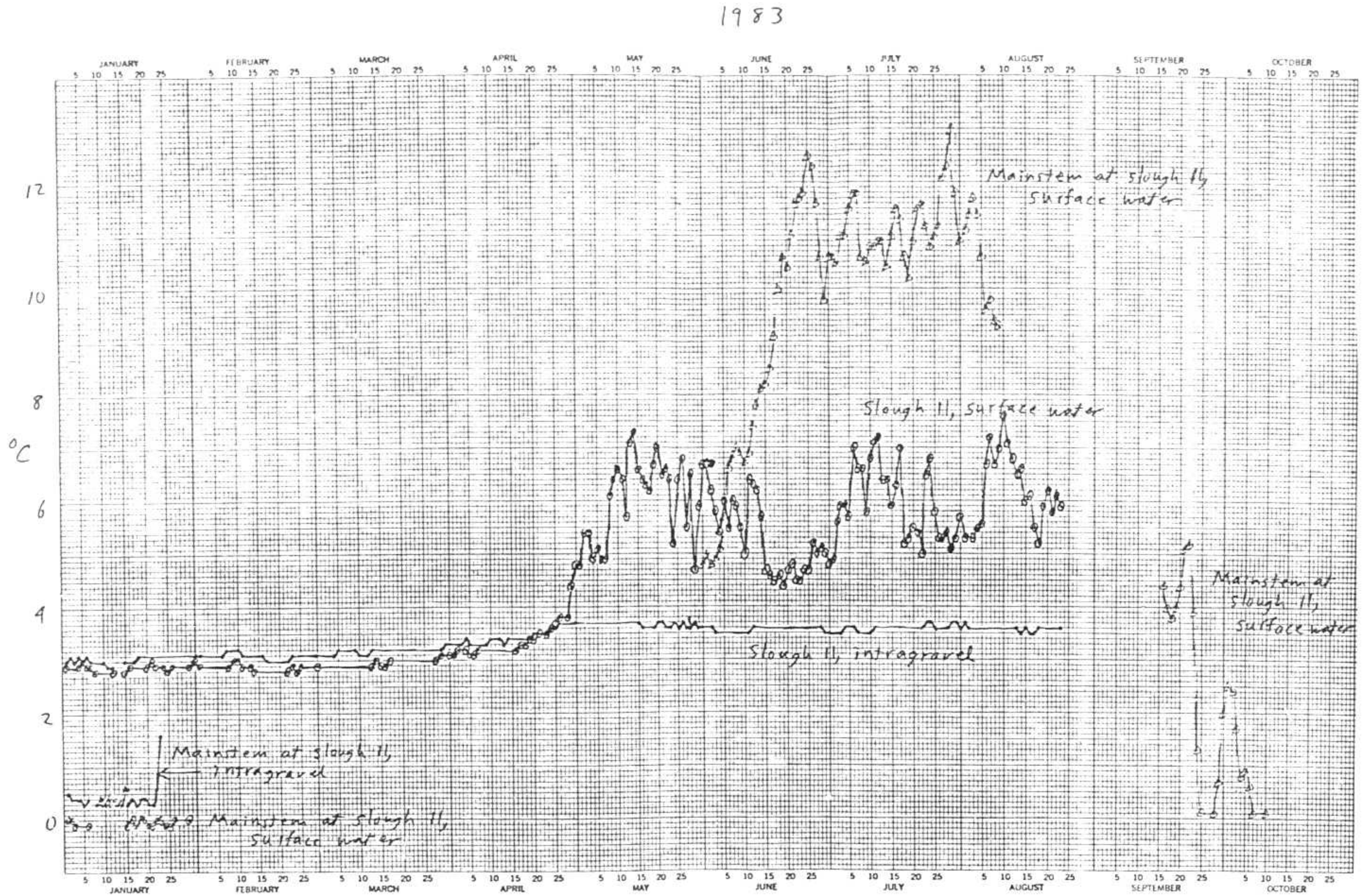
Figure 11. Slough 9 Surface Water and Groundwater Temperatures, 1983

1983 Data



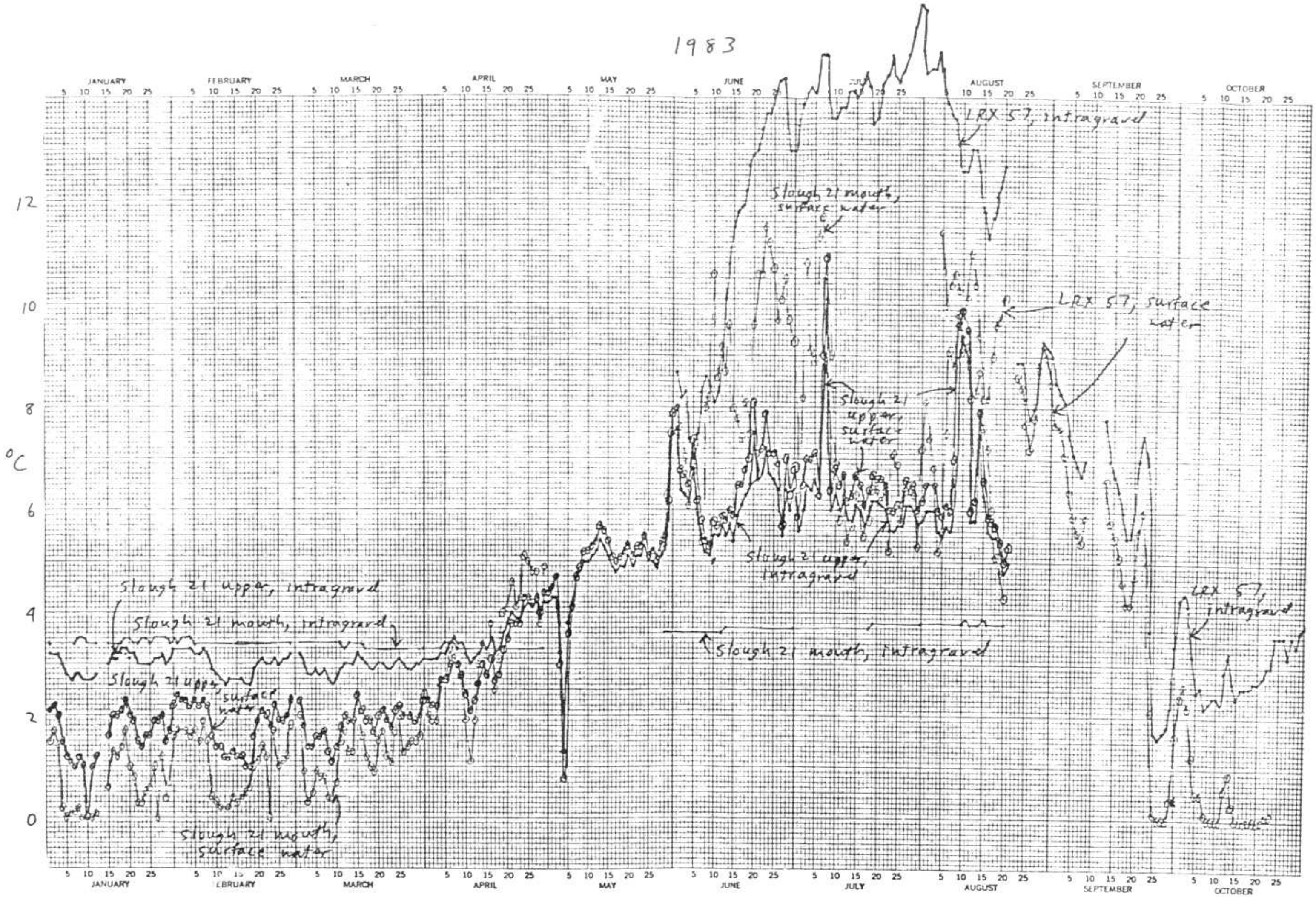
Sources: ADF+G (3)
ADF+G Provisional 1983 Data
R+M Consultants Provisional 1983 Data

Figure 11. Slough 9 Surface Water and Groundwater Temperatures, 1983



Sources: ADF+G (3)
ADF+G Provisional 1983 Data

Figure 12. Slough 11 Water-Temperatures, 1983



Sources: ADF & G (3)
ADF & G Provisional 1983 Data

Figure 13. Slough 21 Water Temperatures, 1983

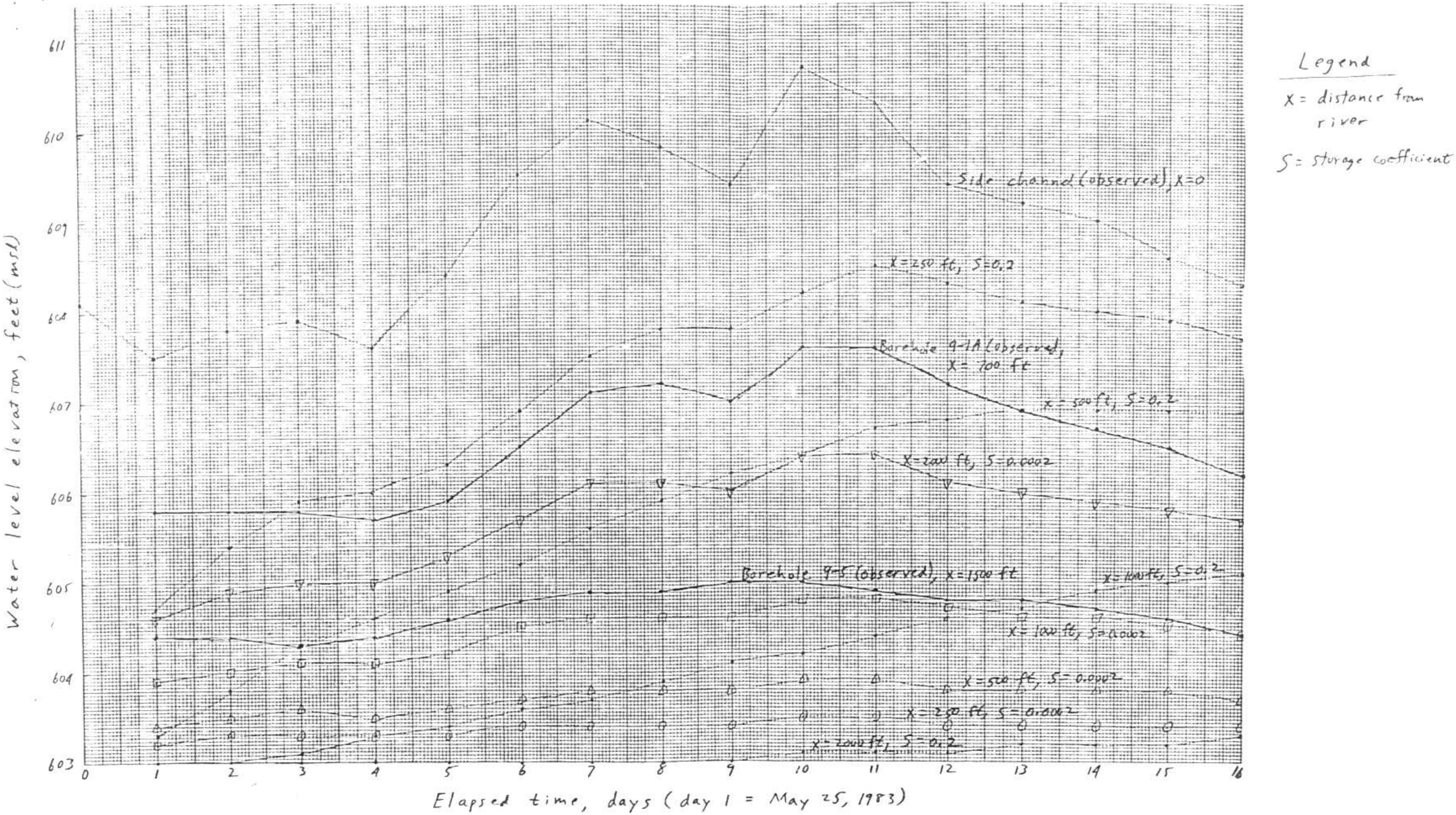


Figure 14. Simulated Groundwater Level Variations in Response to River Stage Variations

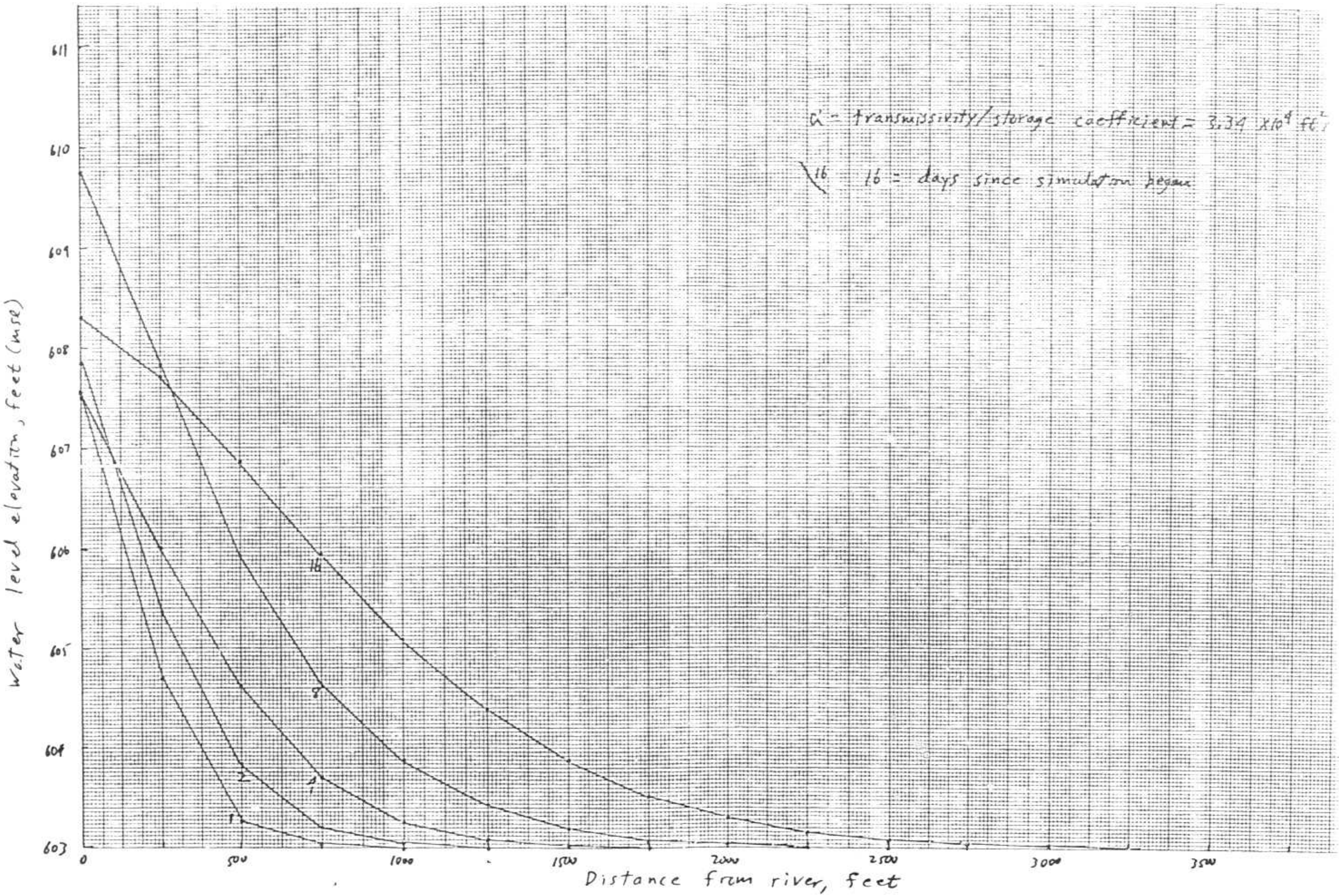


Figure 15a. Simulated Gro
Levels vs. Dista
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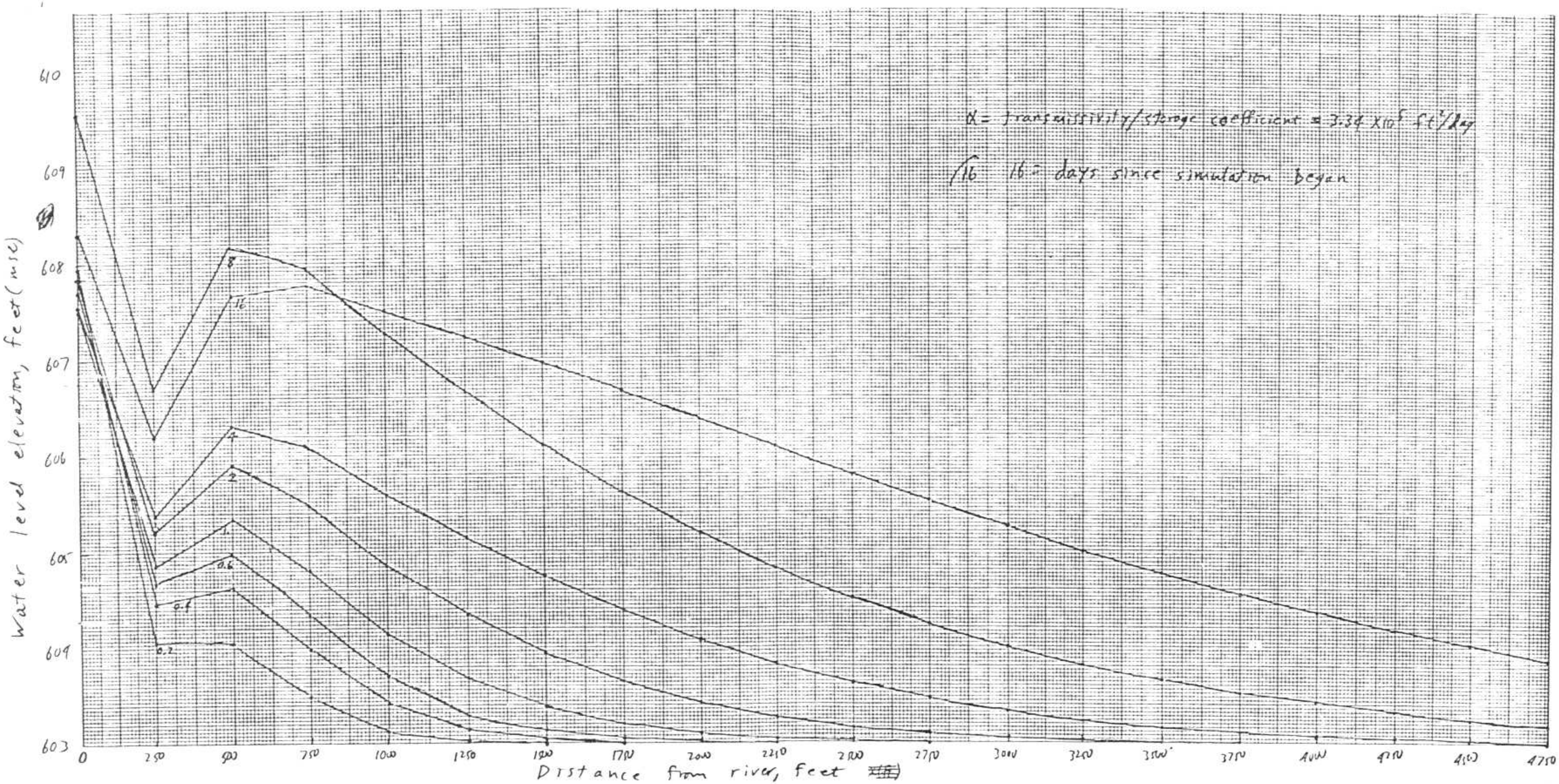

Figure 15 b. Simulated Groundwater Levels vs. Distance from River, Storage Coefficient = 0.02

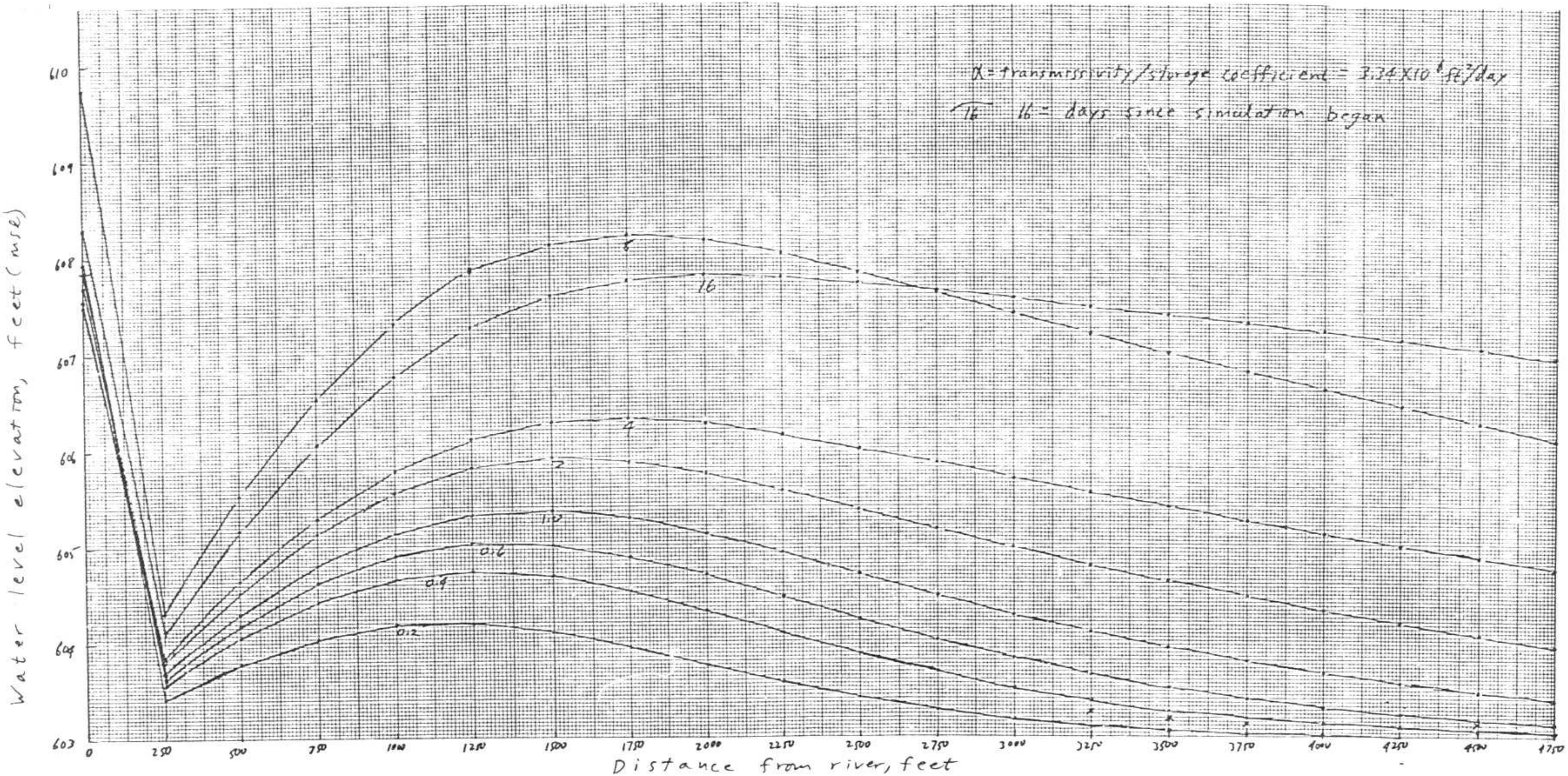

Figure 15c. Simulated Groundwater Levels vs. Distance from River, Storage Coefficient = 0.002

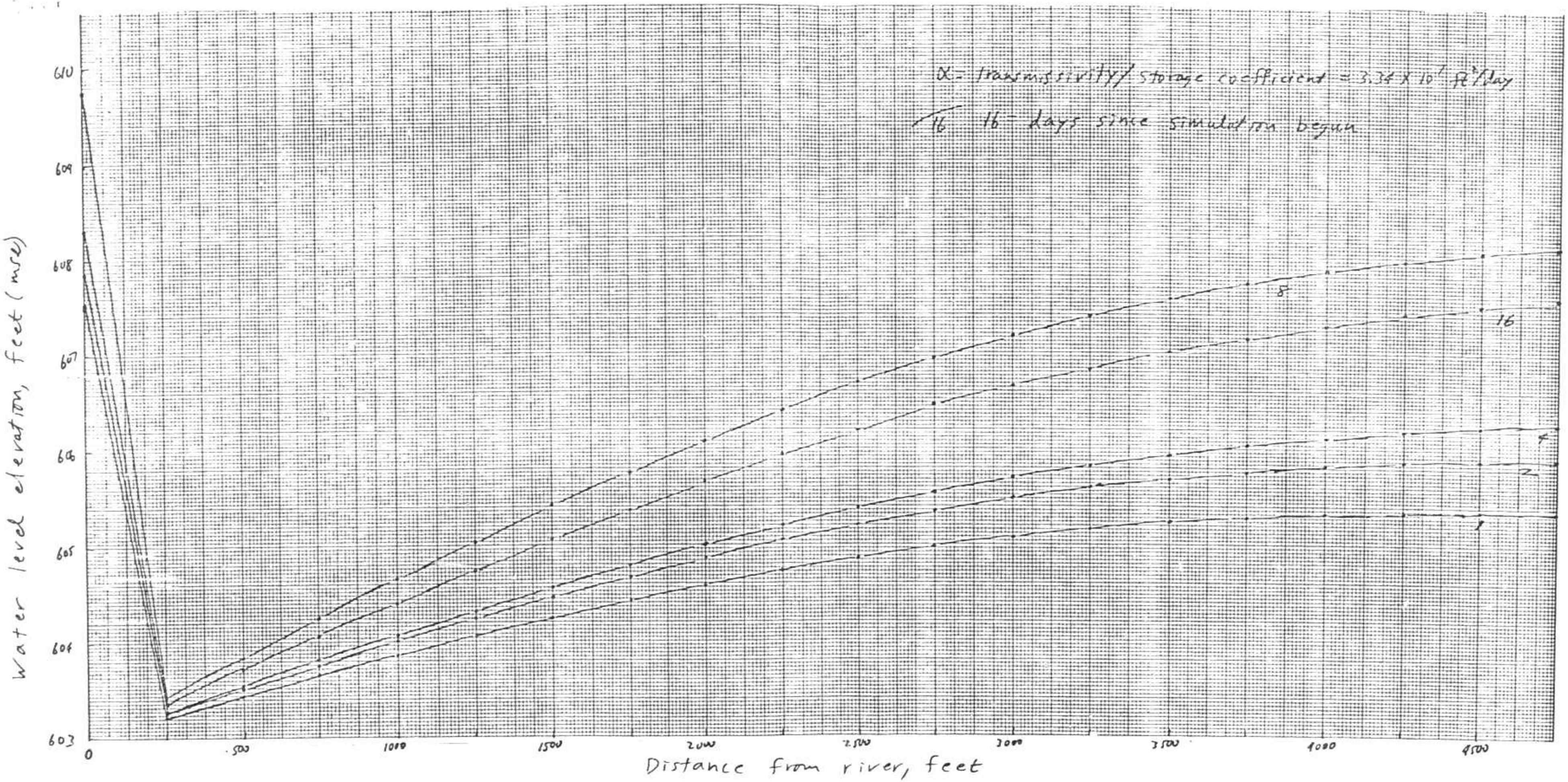

Figure 15 d. Simulated Groundwater Levels vs. Distance from River, Storage Coefficient = 0.0002