SPAWNING SITE HYDROGEOLOGY, ON-SHORE WATER TABLE FLUCTUATIONS DURING LAKE STAGE RISE AND FALL, AND THE EFFECTS OF KERR DAM OPERATION ON SHORELINE HABITAT, FLATHEAD LAKE, MONTANA

Prepared for

Montana Fish, Wildlife and Parks
Kalispell, Montana

By

William W. Woessner
Christine M. Brick
Johnnie N. Moore

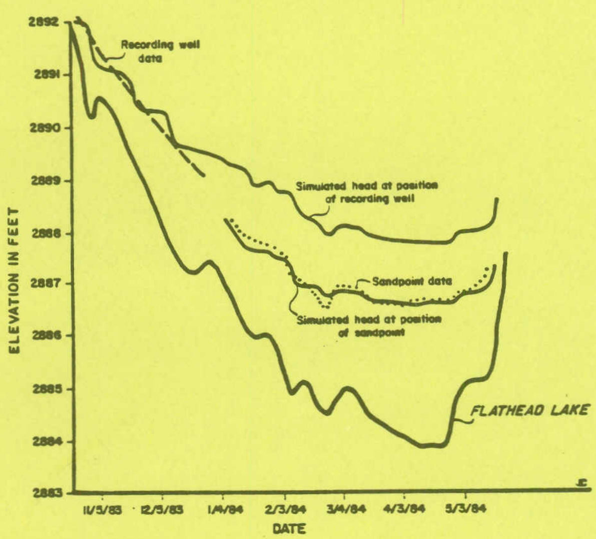

Figure 22: Model calibration, 1983-1984 data.

November 25, 1985
University of Montana
Missoula, Montana

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ABSTRACT

The objective of the report this year is to address three items: 1) A description of the hydrogeologic conditions during spawning and characterization of a generic hydrologic setting, 2) Examination of the effects of lake stage fluctuation on the postion of the water table in spawning sites, and 3) Evaluation of the geomorphic consequences of Kerr Dam operation and shoreline development on spawning habitat. Seepage meter and beach profile data, a numerical two dimensional ground-water flow model and analyses of aerial photography were used to accomplish the stated goals. Spawning sites were grouped into shallow sites, between 2885 and 2882 ft, and deeper sites, to 2871 ft. Apparent velocities at shallow sites ranged from 0.20 to 0.30 cm/hr and from 0.05 to 0.27 cm/hr at deeper sites. Field measurements of DO were generally greater than 8.0 mg/l, though sampling methodology may have elevated DO values. Ground water discharging to spawning sites is dominated by calcuim bicarbonate and ranged in TDS from 114 to 297 mg/l. Numerical modeling of lake stage change ground-water interactions for five FWP grouped periods showed longer periods of exposure during the 1940-1945 and 1976-1983. Redds remained wetted for the longest period of time during 1958-1968. Yearly analysis for the ten year period from 1960 to 1970 was also performed. Analysis of changes in the shoreline features since 1934 for selected portions of the lake revealed that shorelines have changed significantly over the past 50 years. The 1934 to 1937 period was dominated by depositional features while by 1955 nearly all sites examined transformed into areas of active erosion and re-deposition. Data suggest that raising of the elevation of Flathead lake has had a major impact on beach and shoreline dynamics.

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CHAPTER I

INTRODUCTION

This year our report is focused on three topics:

1. Description of hydrogeologic conditions during spawning and the characterization of a generic hydrologic setting;

2. Examination of the effects of lake stage fluctuations on the position of the water table during five periods of dam operation covering several years and yearly from 1960 through 1970;

3. Evaluation of the geomorphic consequences of Kerr Dam operation and shoreline development on spawning habitat.

The report is organized into chapters addressing the three topics specified above: Chapter II, Spawning Site Hydrogeology; Chapter III, Modeling of The Fluctuation of Lake Stage on the Position of the Water Table: Results; Chapter IV, Modification of the Shoreline Resulting from Artifically Raised Lake Levels. The introductory material of Chapter I concludes with a review of the hydrogeologic principles which are necessary to understand the distribution and variation in shoreline apparent velocity measurements.

BACKGROUND

This section is separated into five sections: 1) The Flathead Lake Hydrogeologic System; 2) Factors Affecting the Rate of Ground Water Flow to the Shoreline; 3) Factors Affecting Apparent Velocity Measurements in the Beach Area; 4) Factors Affecting the Distribution of Apparent Velocity in the Lake Sediments and 5) Summary.

Flathead Lake Hydrogeologic System

In 1983 we proposed a regional hydrogeologic conceptual model which showed Flathead Lake as a regional and local ground water discharge area (Figure 1)(Woessner and Brick, 1983). This model is supported by the results of three years of hydrogeologic research on the shoreline ground-water system. Ground-water flows to the lake from the higher topography. The ground-water system is annually recharged by spring snow melt and precipitation. Streams flowing from the adjacent bedrock highs become influent, recharging the unconsolidated sediment adjacent to the lake shore throughout the year. The lake surface contact with the shore marks the separation of the ground-water recharge area and the zone of discharge. Ground water generated upland of the shore and flowing to the lake discharges below the lake surface through the lake bottom (Figure 2). The actual rate of discharge and its spatial and temporal distribution are a function of a number of hydrogeologic factors. In the following sections we describe the hydrogeologic processes controlling ground-water flow and discharge in the Flathead Lake shore area. The discussion also includes an analysis of the effects of varying the lake stage as a result of dam operation.

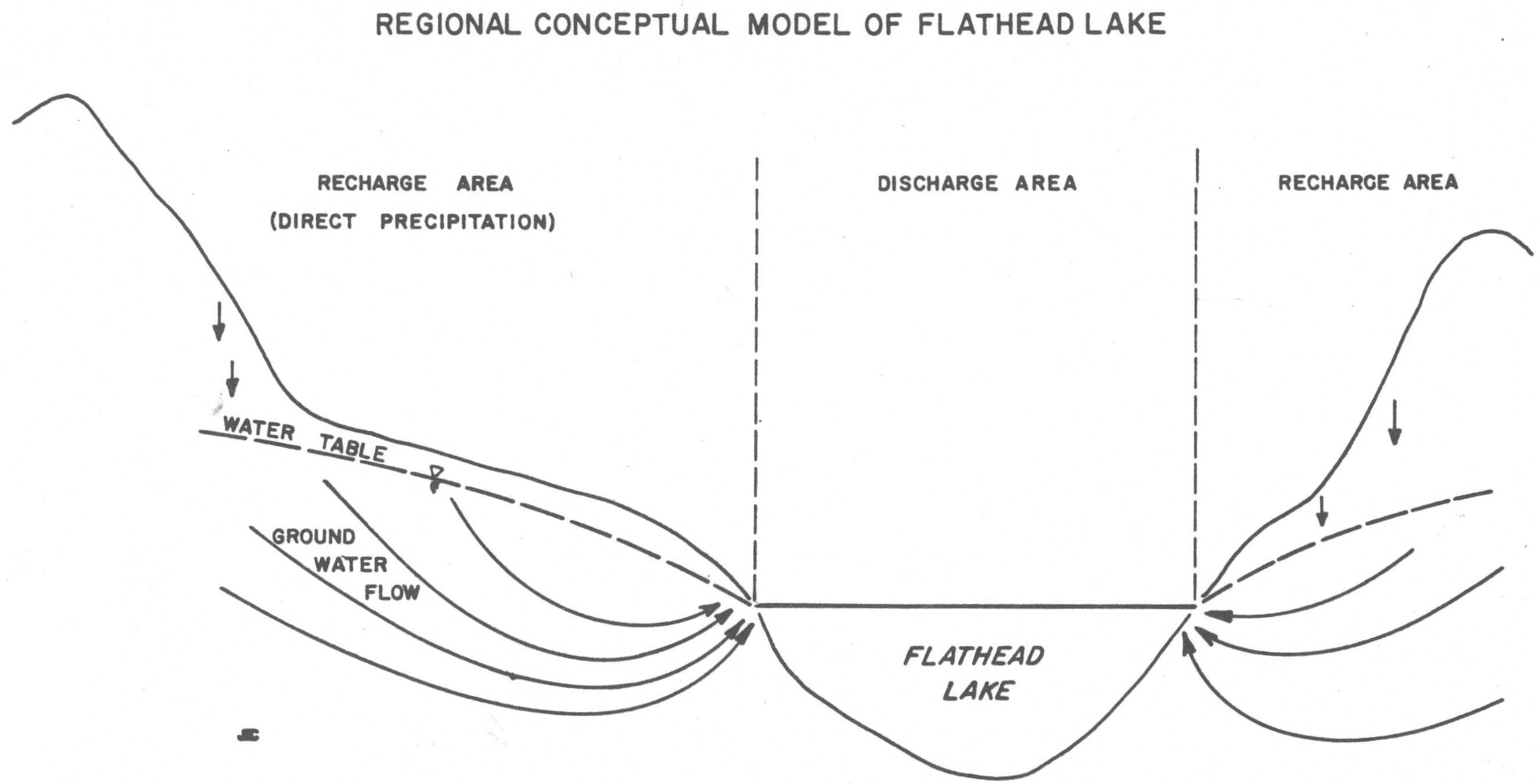


Figure 1: Regional conceptual model of Flathead Lake.

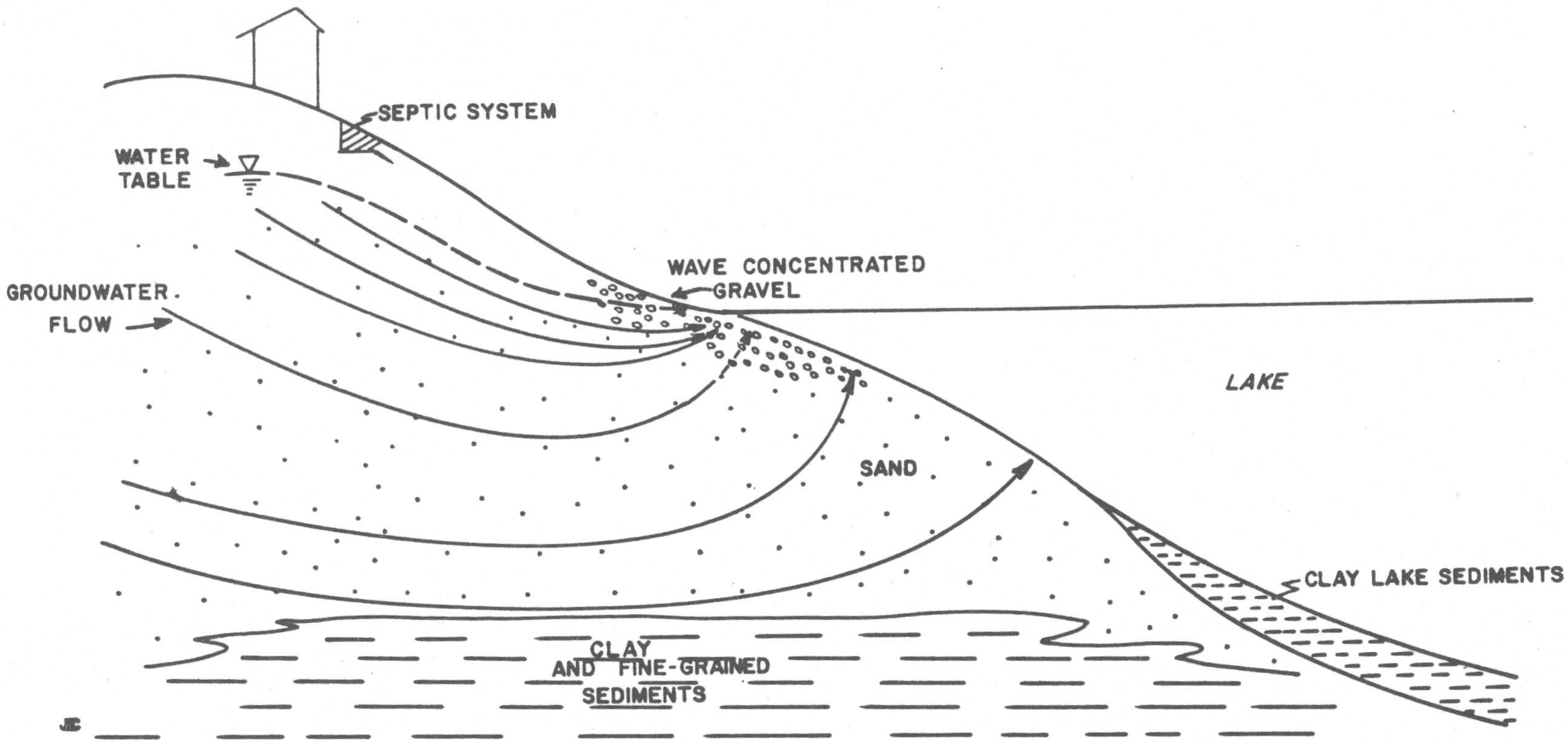


Figure 2: Shoreline flow system.

Factors Affecting the Rate of Ground-Water Flow to the Shoreline

The rate at which ground water flows through earth materials is a function of the size and interconnectedness of pores in the geologic material, the hydraulic gradient or slope of the water table surface and the size of the cross sectional area. In 1856 Henry Darcy described ground-water flow in simple, one dimensional, steady state terms:

$Q = -KiA$ where: Q is the discharge of ground water, l^3/t
K is the hydraulic conductivity, l/t
i is the hydraulic gradient, l/l
A is the cross sectional area of aquifer perpendicular to the direction of flow, l^2

This equation is used to describe flow in a confined aquifer or porous media with little change in thickness (Figure 3). The minus sign is a convention which illustrates that the gradient is measured in the direction of decreasing energy or water level. Further modifications of this equation, known as Darcy's law, include a version specifically for water table aquifers in which the thickness of the aquifer decreases in the direction of flow because the top of the aquifer is defined as the water table (Figure 3). For our modeling efforts we used a two dimensional version of the water table equations; however for our general discussion in this section, the equation for the confined aquifer will suffice and be easier to work with.

The discharge of ground-water, i.e. the rate of delivery of ground water, is a function of the slope of the water table and the physical composition of the sediments through which flow is occurring. If we take a closer look at $Q = -KiA$, the discharge (gal/day) of an aquifer is directly proportional to the hydraulic conductivity, hydraulic gradient and cross-sectional area. An increase in any one of the factors when the others are held constant will result in an increase in discharge. For example, recharge to the water table system would raise the water table steepening the hydraulic gradient (i) which would result in an increase in discharge.

The hydraulic conductivity of earth materials is a function of the quantity and size of interconnected pore spaces, assuming that water temperature is constant. In bedrock, the hydraulic conductivity is a function of the amount of fracturing. In glacial tills, fluvial sediments and beach deposits, it is dependent on the size, sorting and packing of the sediments. The better sorted, more loosely packed and the larger the size and number of interconnected void spaces, the higher the hydraulic conductivity. Wave action removes fines from the clay rich shoreline glacial tills. The resulting beach deposits have higher hydraulic conductivities than the original material making up the shoreline. However, fine material sorted from the wave zone is typically redeposited off shore. This material and the settling of fines suspended in the lake result in the clay rich low hydraulic conductivity sediments found over most of the lake bottom. Unless glacial material adjacent to the shore is initially well sorted and coarse grained, on-shore sediments would generally be lower in hydraulic conductivity than beach deposits. Darcy's Law assumes that the porous material has uniform hydraulic conductivity. A more complicated equation allows the variation in hydraulic conductivity to be represented in three dimensions. Figure 2 illustrates the heterogeneous nature of the shoreline areas. To be correct,

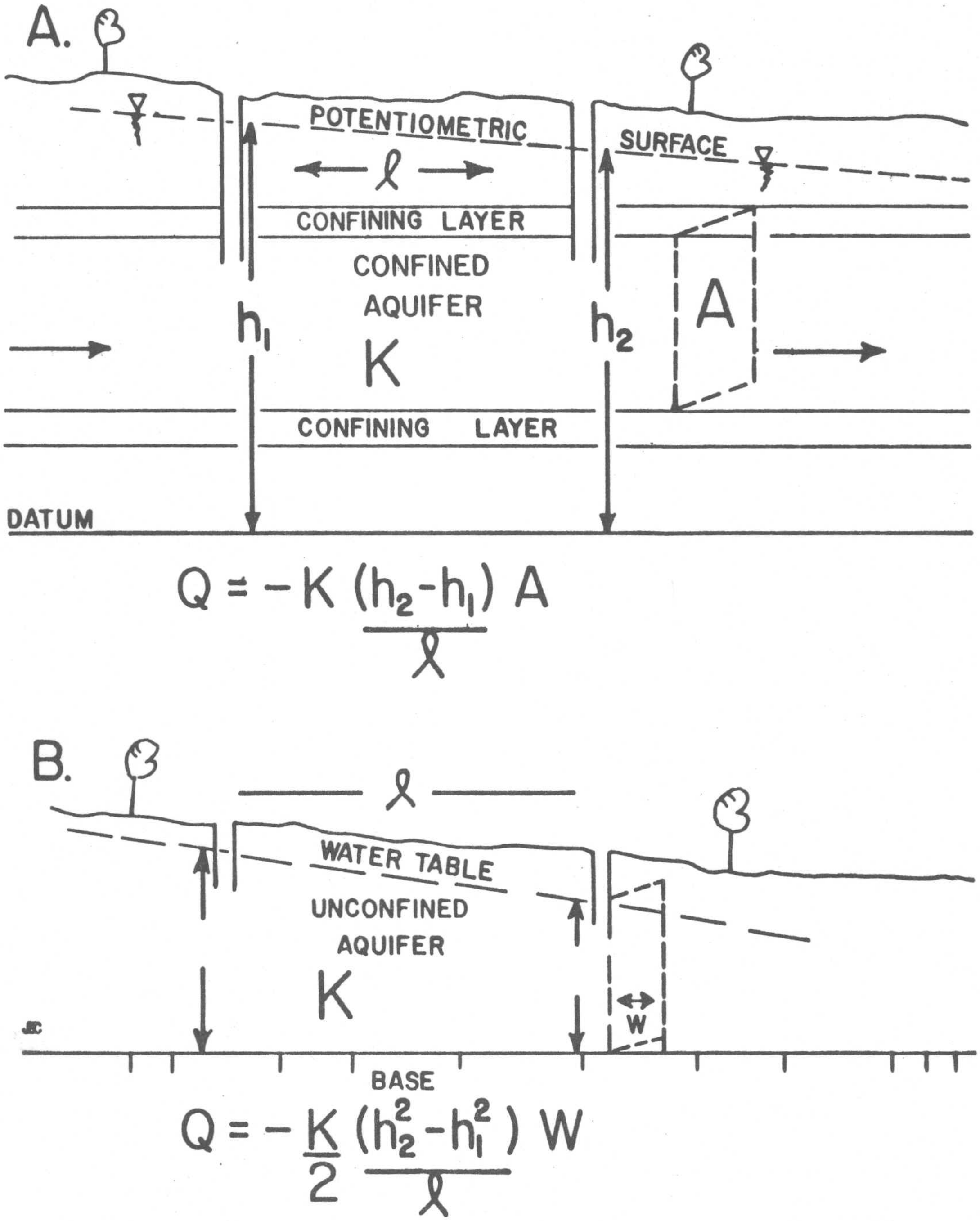


Figure 3: Steady state, one dimentional ground-water flow equations: A. Confined aquifer and B. Unconfined aquifer.

calculation of discharge using the one dimensional version of Darcy's Law would require a weighted value of K to reflect the non-homogeneous nature of the sediment. Natural variations in the hydraulic conductivity of shoreline materials and the resulting ground-water flow are expected because of the complex glacial and post glacial history of the region.

A change in the hydraulic gradient will also affect the rate of flow in the aquifer. The gradient is in part a function of the local and regional climate. The rate and quantity of recharge available to the ground-water system and the aquifer's ability to transmit water will control the seasonal build up of the water table with the highest level usually occurring in the spring. As water recharges the system, the hydraulic gradient steepens and the rate of flow increases. In western Montana, the majority of recharge from precipitation comes in the spring. After June, little precipitation reaches the water table. As a result, the discharge of ground water into the lake slowly begins to decline as the water table declines. The water table decreases its slope in response to the lack of recharge. This process is offset by stream infiltration in areas where streams cross unconsolidated sediments. The rate of recharge is often sufficient to maintain a constant water table slope in the beach area.

A second process which complicates the delivery of ground water to the beach area is the seasonal raising and lowering of the lake stage. This process has the effect of steepening the gradient to the beach in some areas in the fall and winter when normally we would expect a reduction in water table slope and ground-water discharge. The raising of the stage in late April and May, a time which also corresponds with upland snowmelt recharge and gradient steepening, has the effect of damping the natural steepening of the water table.

Wells withdraw water up-gradient from the shore area also locally depress the water table. If withdrawls are close to the beach area and large enough to significantly depress the water table shoreward, hydraulic gradients may be measurably lowered, reducing discharge to the lake or even locally reversing the direction of flow. Homeowners and businesses also pump water from the lake for potable water and lawn and orchard irrigation. The infiltrating irrigation water and septic system discharge result in increased recharge to the local system. The increase in recharge would result in a steepening of the gradient and an increase in discharge to the lake. Conversely, the withdrawl of ground water would reduce discharge to the beach area. In the Flathead Lake area, the recharge to local areas by septic systems is probably measurable, however, pumping and irrigation effects are negligible.

Most of the previous discussion assumes that the cross sectional area of flow remains constant. However, if we examine a cross sectional area parallel to the shoreline with the lake-shoreline contact as an upper boundary, the cross sectional area would change with lake stage fluctuation. The 10 ft decline in lake stage during the fall and winter results in a reduction in the cross sectional area. The lake stage rise in the spring enlarges the cross sectional area for ground water flow. As stated by Darcy's Law these changes in lake stage would result in a decrease and then an increase in ground-water discharge if all other factors were held constant.

A description of the factors affecting the rate of ground water delivery to the shore area is obviously complicated by seasonal and spatial variablity in recharge, lake stage fluctuations and spatial variations in the hydraulic conductivity. At a given location, hydraulic conductivity is the only fixed property. The hydraulic gradient and cross sectional area in the shore area are functions of climate and yearly dam operation.

Factors Affecting the Apparent Velocity Measurements in the Beach Area

Apparent velocity is an expression of ground-water discharge with the cross-sectional area divided out. The apparent velocity of a ground-water system is described by a re-arrangement of Darcy's Law:

$v^* = Q/A = Ki$ where: Q, A, K and i are previously defined
v^* is the apparent velocity, l^3/tl^2

Apparent velocity is the flux of ground water through a unit area of aquifer (Figure 4). It is called an apparent velocity because its units reduce to length divided by time which is velocity. This velocity, however, is not the true rate of ground-water flow because the water moving through a unit cross sectional area of aquifer only flows through the interconnected pore spaces (Figure 4). To avoid confusion, apparent velocity should always be thought of in terms of flux not velocity.

Measurement of apparent velocity in the beach area is most easily done by determining the hydraulic conductivity of the sediments and, with the aid of shallow wells, the hydraulic gradient at a given time. Theoretically, because K is a function of the porous media and fluid only, a single measurement at a well should suffice. Methods to determine K were previously described by Woessner and Brick (1983). Measurement of the hydraulic gradient is accomplished by placing sandpoint wells in the beach just below the water table and determining the change in water table elevation between two points in the direction of flow. If the aquifer is assumed to be homogeneous, the direction of ground-water movement will be in the direction of the greatest hydraulic gradient.

Factors affecting the measurement of the apparent velocity of a beach aquifer have been addressed above. Values would be expected to change with time as the natural hydraulic gradient responds to recharge and discharge. Figure 5 illustrates the flow paths of ground water in a vertical cross section constructed parallel to the direction of flow. Measurement of apparent velocity immediately below the water table in the shore will yield the largest values. Measurement of apparent velocity at the lake-bottom interface yields lower values because the ground water is flowing along a longer flow path under the same change in water table elevation, thus reducing the gradient and the apparent velocity. Finer grained and more poorly sorted sediments on the lake bottom have a lower K which results in further reduction of off-shore measured apparent velocities. In addition, the effects of the lake rise and fall will also be reflected in the observed apparent velocity values.

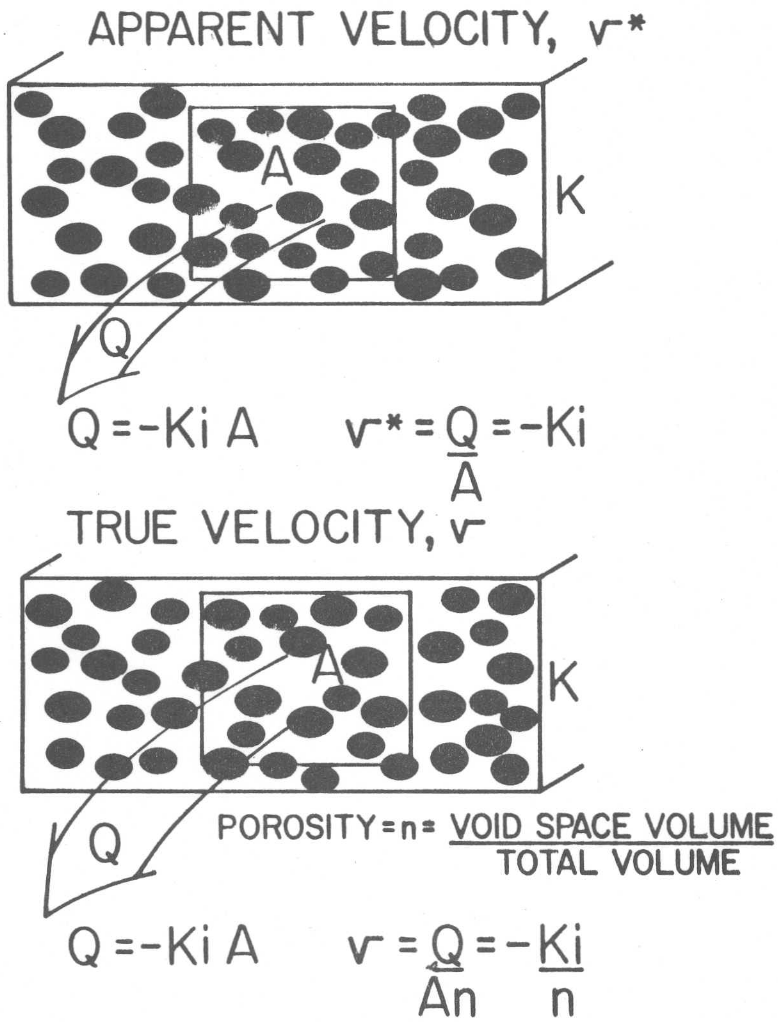


Figure 4: Calculation of apparent velocity and true ground-water velocity.

Factors Affecting the Distribution of Apparent Velocity in the Lake Sediments

The distribution of ground-water flow through the lake bottom is a function of the distance from shore, hydraulic conductivity of the lake sediments and the slope of the lake bottom. The rate of discharge at any one point is also dependent on the on-shore ground-water system and all the factors affecting its rate of flow to the lake.

Calculation or measurement of K and i is difficult for the submerged lake bottom sediments. Flow at the bottom-lake interface is basically vertical (Figure 5). A measure of the vertical hydraulic conductivity of the sediment column is needed in addition to the quantification of the upward vertical gradient within the lake sediments. Apparent velocity measurements are made by determining the discharge, Q, through a fixed cross sectional area which is perpendicular to the direction of ground-water flow and parallel to the lake bottom, A. The seepage meter is used to determine discharge, Q, and v* is calculated by dividing Q by A (Woessner and Brick, 1983).

A cross section of the lake shore in the direction of flow is presented in Figure 6. Assuming the sediment transmitting water to the lake shore is homogeneous, the flow paths become longer with distance from shore. The apparent velocity measured by seepage meters at sites A, B and C shows a logarithmic decline in flux with distance from shore. This is because the hydraulic gradient becomes smaller and smaller as the ground-water flow path becomes longer, thus v* decreases (Figure 6). The clay layer represented in the diagram represents fine lake sediments below the active wave base which have a low hydraulic conductivity. Numerous researchers have documented the logarithmic decrease in apparent velocity which is typical in lake discharge areas. The discharge area and relative apparent velocities measured at the same three distances from shore are also presented in Figure 7. The only difference represented is a steepening of the slope. The steep slope results in a shortening of the ground-water flow path and an increase in the rate of ground-water discharge at all sites. Ground-water discharge in an area with an irregular slope would also decrease with distance from shore but apparent velocity values would not necessarily be logarithmic (Figure 8).

The rate of ground-water discharge to Flathead Lake is also affected by the 10 ft lake stage fluctuation. A reduction in lake stage would increase the apparent velocity at a deeper meter if the water table slope was maintained or steepened (Figure 9). The apparent velocity measurements at the same site on the lake bottom would decrease during lake stage rise as flow paths would lengthen (Figure 10). A change in the hydraulic gradient in response to natural recharge or lake stage fluctuation would also alter the apparent velocity measured at any one point on the lake bottom. Figure 11 shows the effect of a lowered water table on the apparent velocity measured at sites A, B and C.

In each of the situations listed above, the hydraulic conductivity was assumed to be constant. In actuality, however, the beach sediments are not homogeneous so hydraulic conductivity varies both laterally and vertically. The area with higher hydraulic conductivities will have large values of apparent velocities if the same recharge and flow path lengths are maintained. The actual anisotropic nature of the sediments further complicates ground-water flow in the lakeward sediments. In areas where the ratio of the horizontal to vertical hydraulic conductivity is large, flow paths are

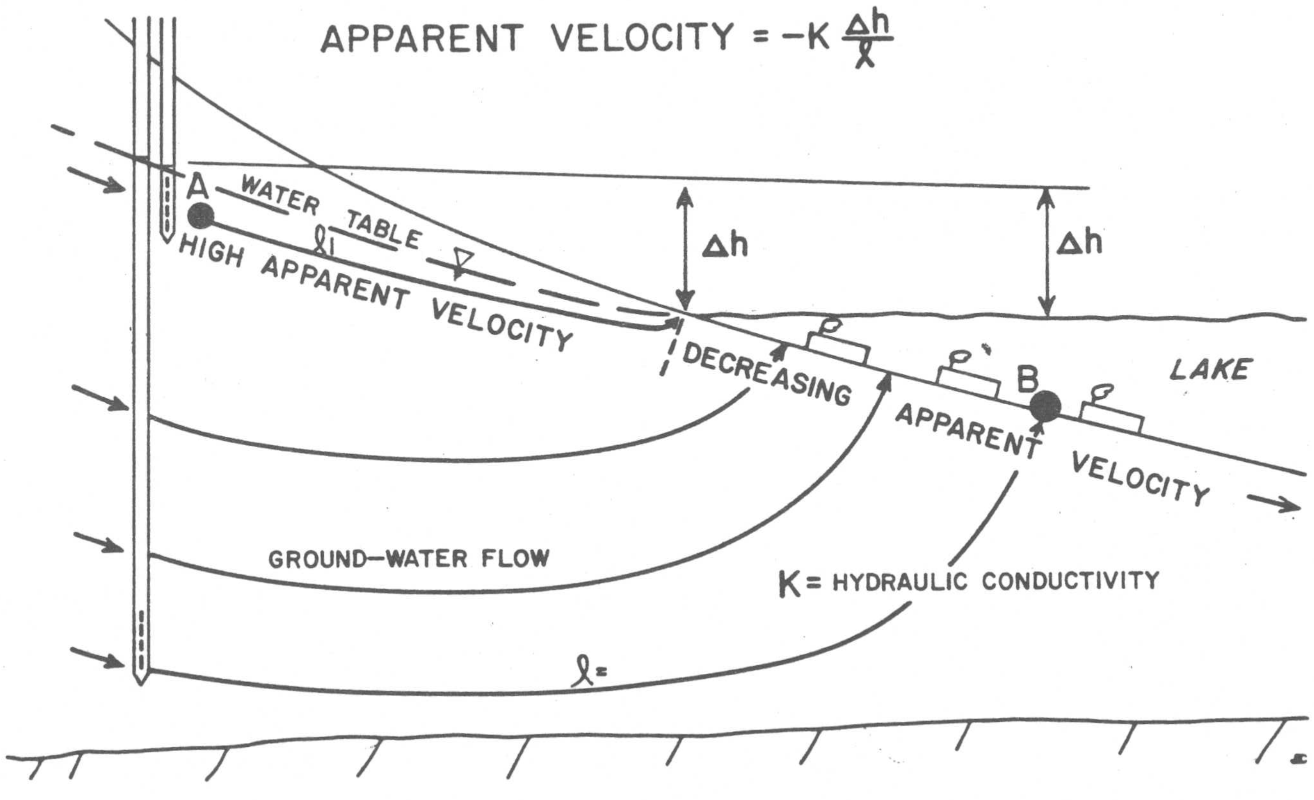
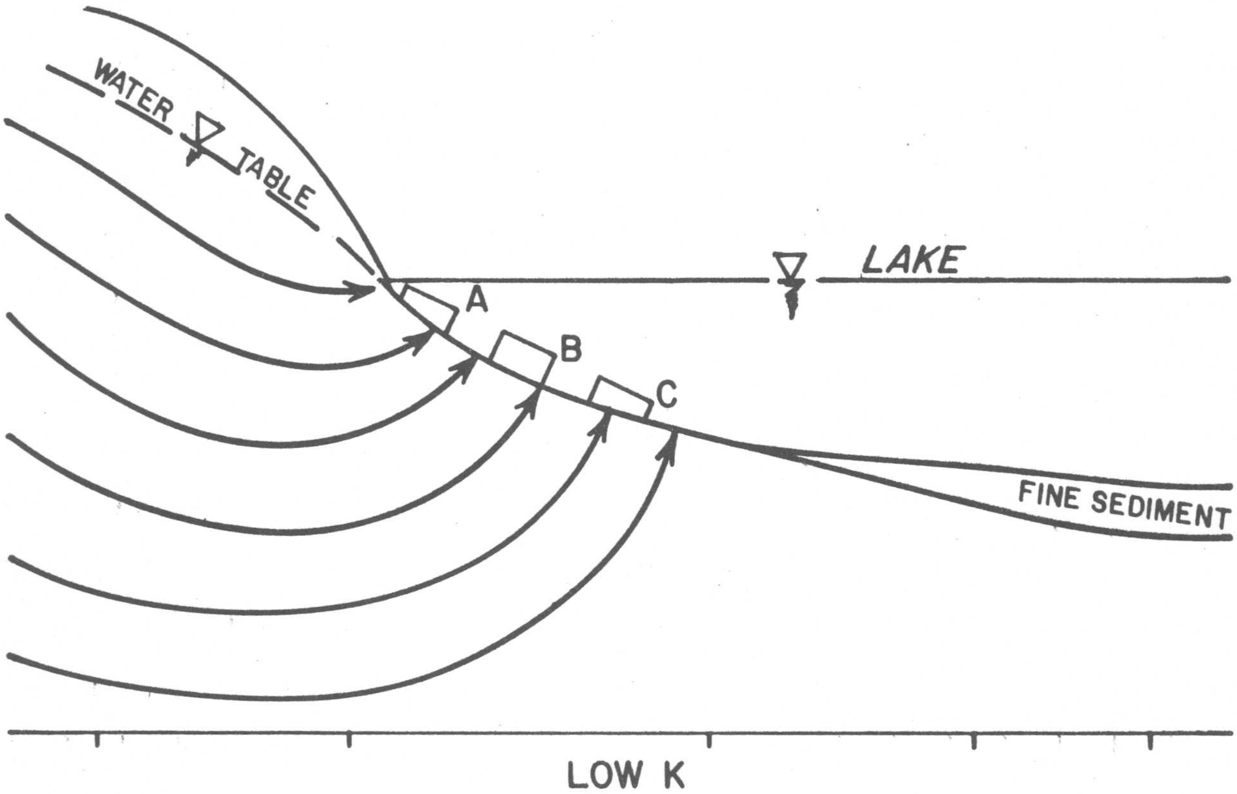


Figure 5: Schematic of beach area. Apparent velocity is higher at A than at B.



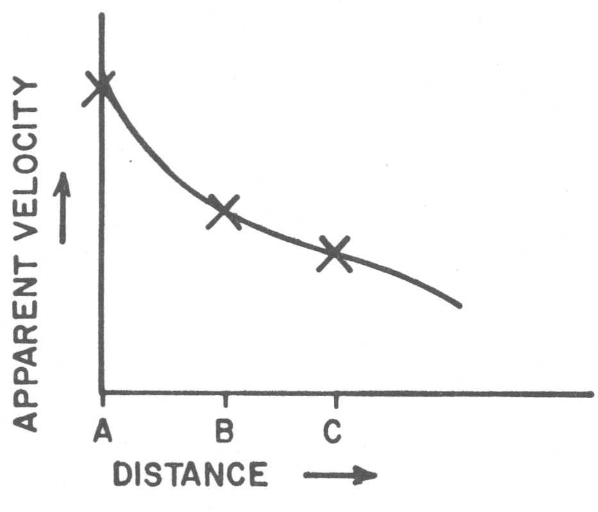


Figure 6: Distribution of flow and apparent velocity.

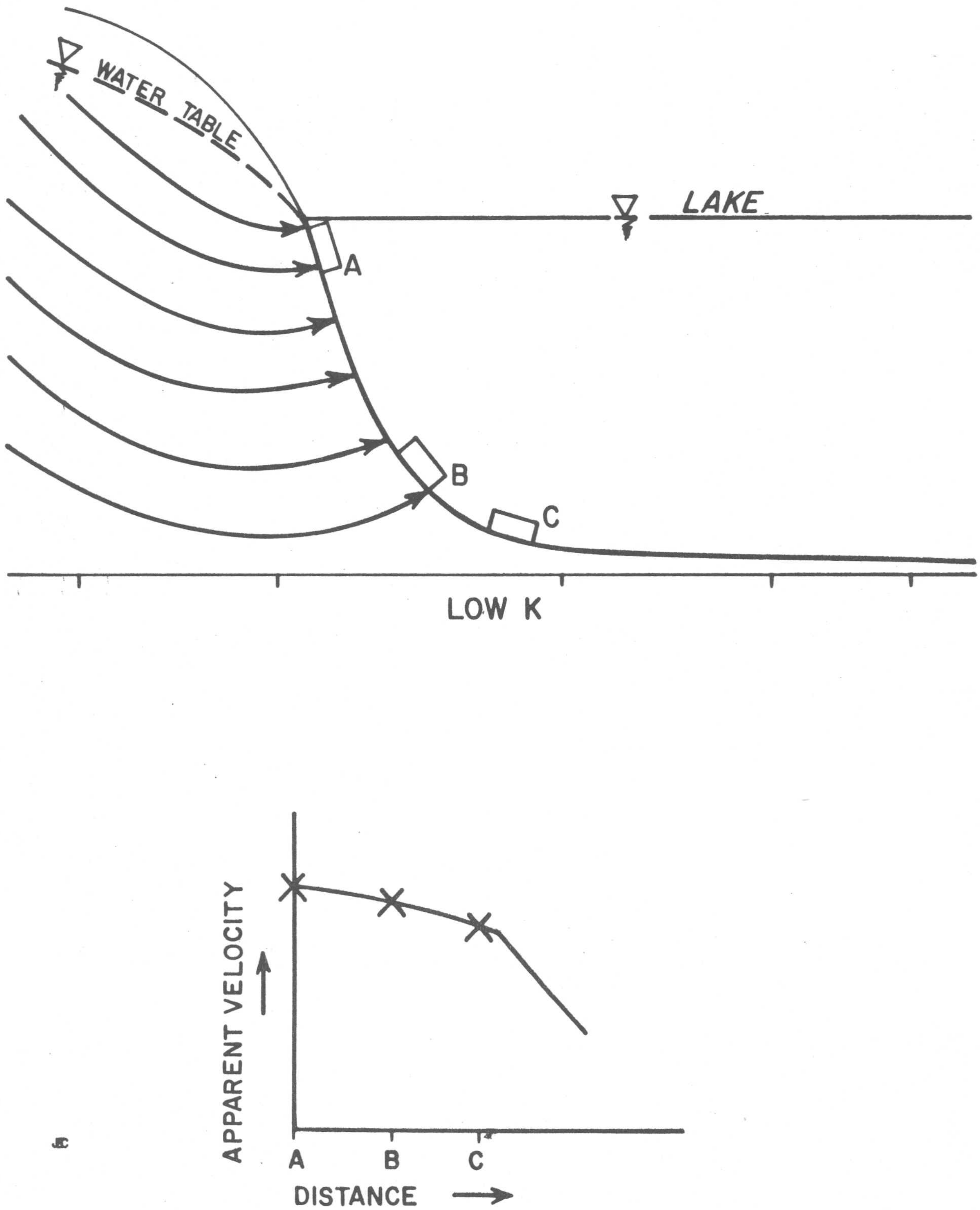


Figure 7: Distribution of flow and apparent velocity with a steep profile.

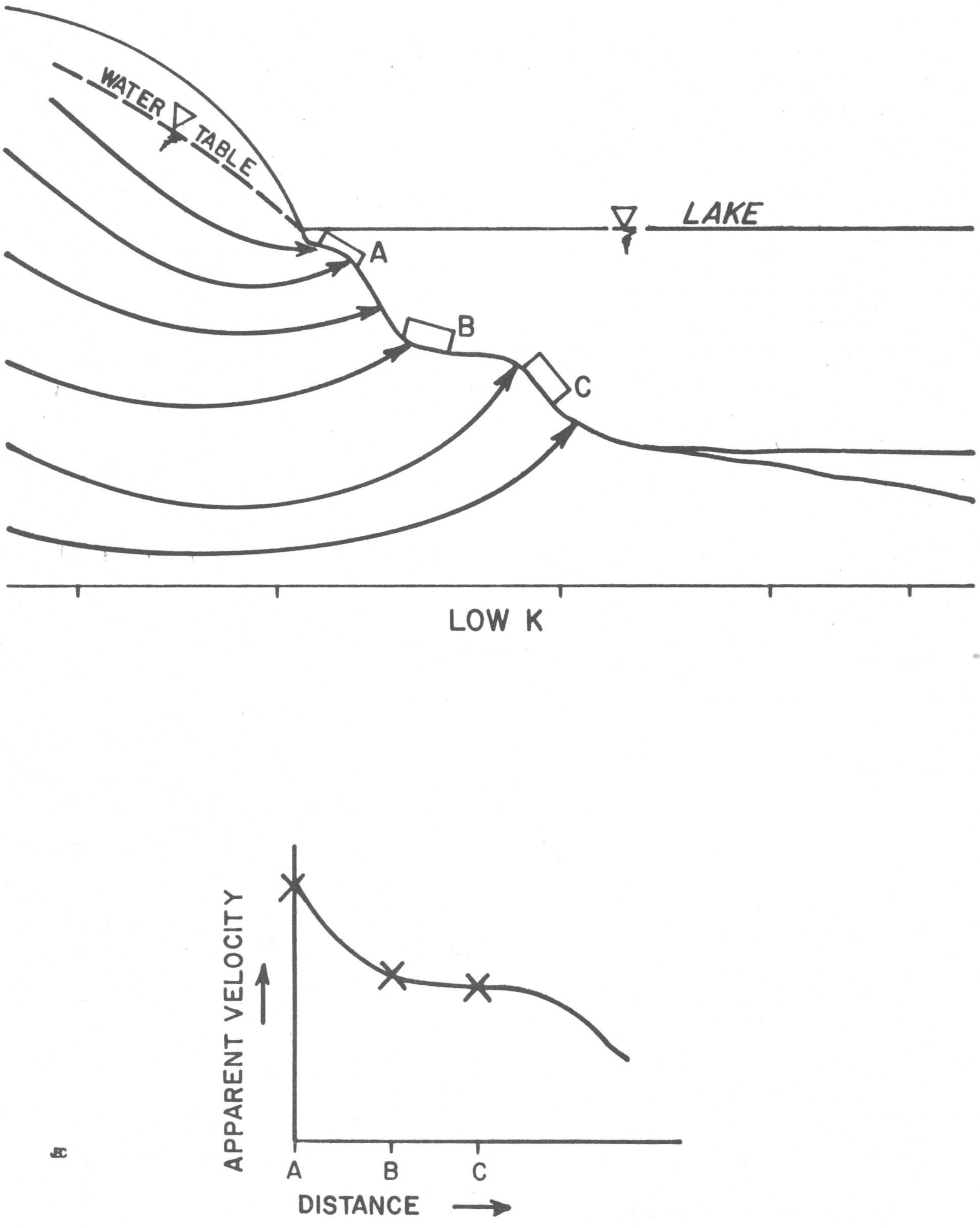
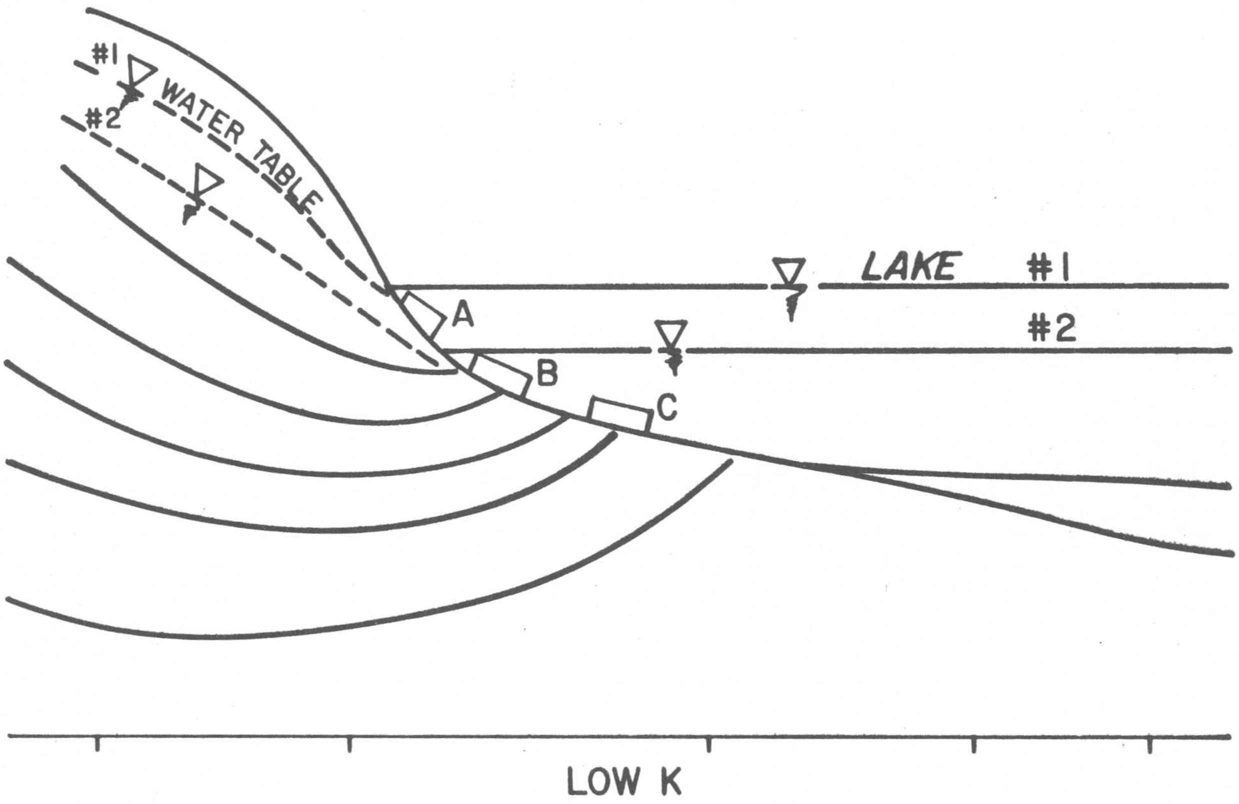


Figure 8: Distrubution of flow and apparent velocity, irregular profile.



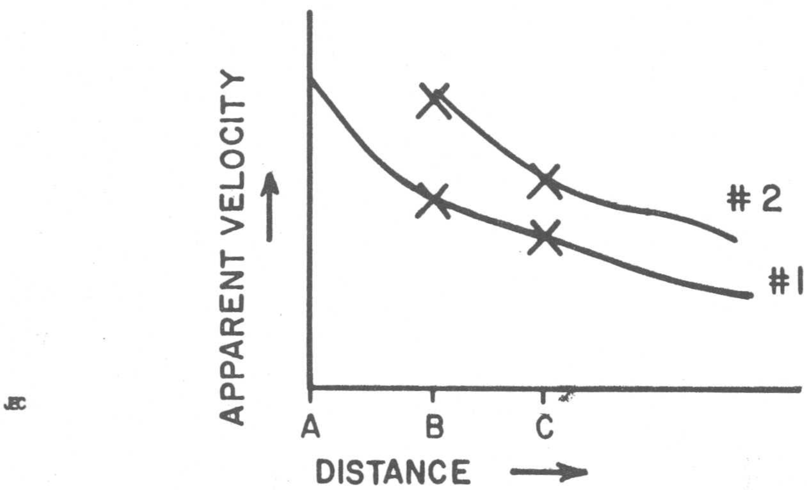
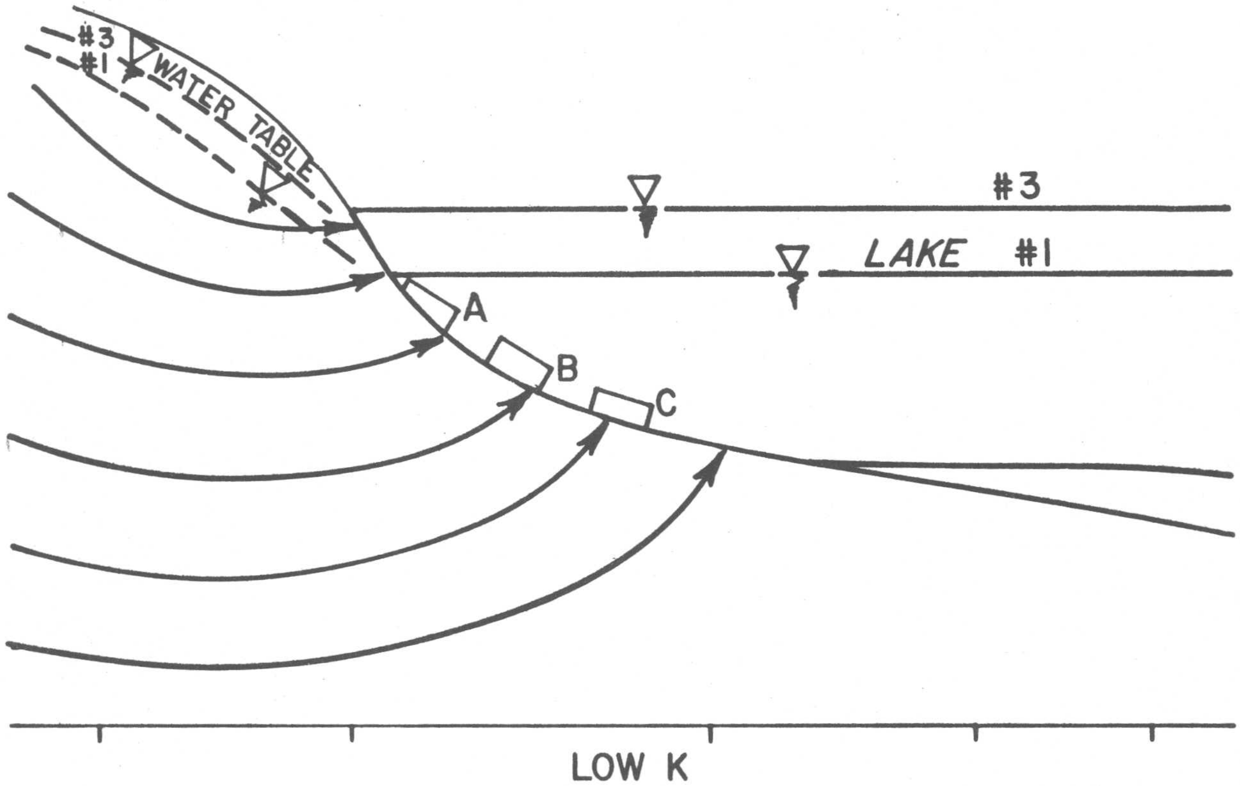


Figure 9: Distribution of flow and apparent velocity, lake stage decline.



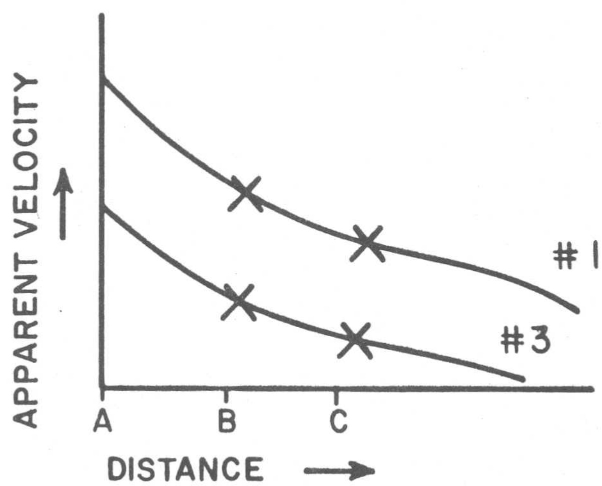


Figure 10: Distribution of flow and apparent velocity, lake stage rise.

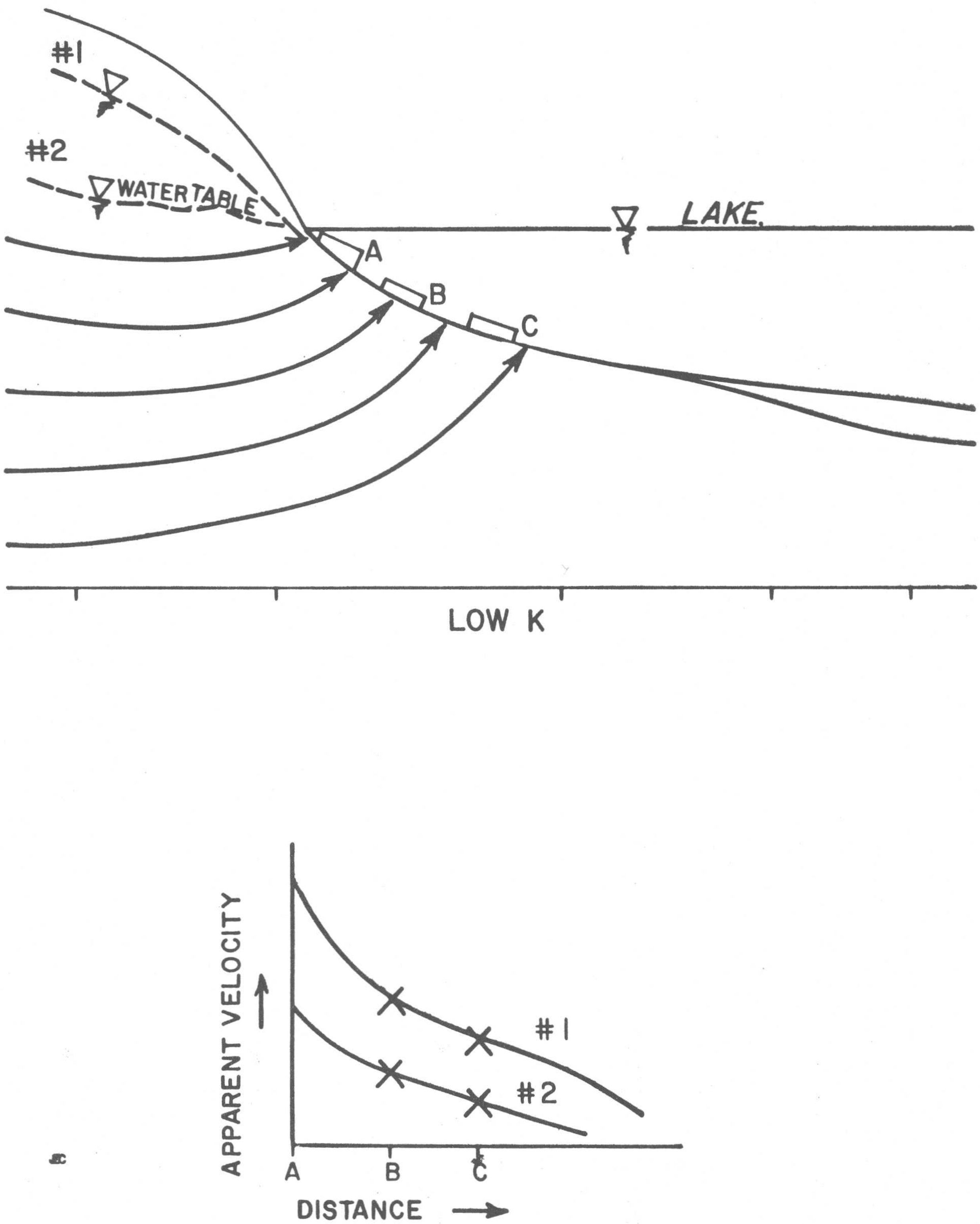


Figure 11: Distribution of flow and apparent velocity, water table decline.

concentrated in the horizontal plane. This results in greater seepage occurring on the more vertical or more steeply sloped portions of the lake bottom (Figure 12). Apparent velocity for sections of steep slopes can be higher than adjacent meters located in flatter portions of the slope closer to shore under these conditions.

Summary

Determination of the apparent velocity of ground-water in the beach area or in the submerged lake sediments is relatively easy. However, to evaluate the spatial and temporal variation in the measured values, a detailed understanding of the dynamics of ground-water flow to the lake shore is required. The varation in apparent velocity depends on the distribution of hydraulic conductivity, fluctuations in hydraulic gradient, and variations in cross secitonal area. All of these factors must be well understood before generalizations about the ground-water system can be made and hydrogeologic forecasting attempted.

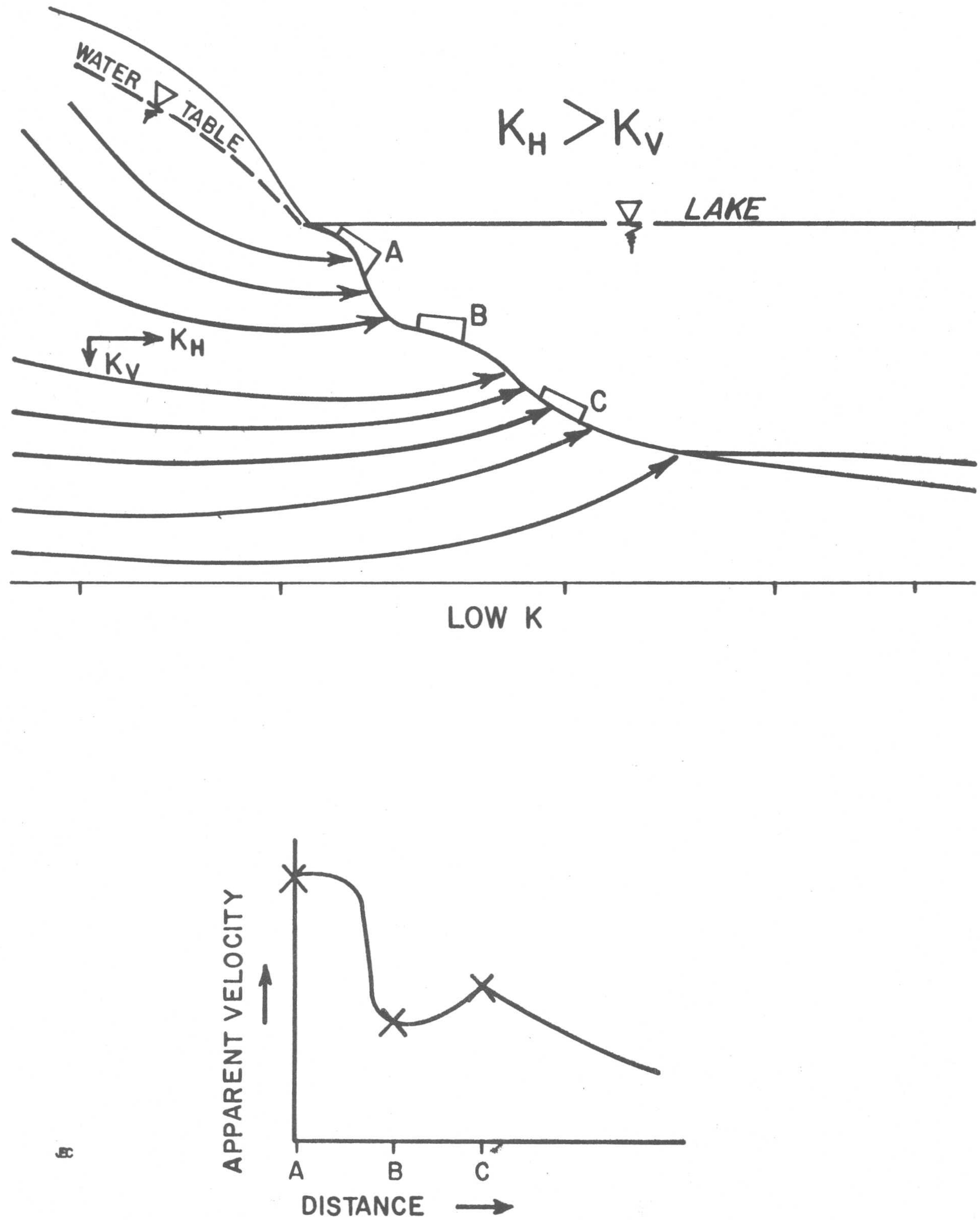


Figure 12: Distribution of flow and apparent velocity, horizontal hydraulic conductivity is greater than vertical hydraulic conductivity.

CHAPTER II

SPAWNING SITE HYDROGEOLOGY

Introduction

The description in Chapter I of the factors affecting apparent velocities measured in submerged beach gravel during spawning emphasizes the difficulty of attempting to generalize "typical" or generic spawning site hydrogeology. In the past three years we have obtained measurements of apparent velocities during spawning at 16 sites on Flathead Lake and at one site each in Ashley Lake and Swan Lake. Dissolved oxygen data were also collected at 10 spawning sites in conjunction with the seepage velocity data. The information collected in 1984 is the most comprehensive and forms the basis for the majority of our analysis.

Fall kokanee spawning occurs from October through December each year. In Flathead Lake, spawning fish occupy sites immediately adjacent to shore in two to seven feet of water and at some sites, use gravel to depths of 27 ft. Fifty nine percent of the redds were located between 2883 ft and 2888 ft, shallow sites, and the remainder between 2883 ft and 2869 ft, deep sites. In 1984 a total of 719 redds were counted at 17 shoreline sites (Decker-Hess and Clancy, 1984) (Figure 13). This is compared with 592 redds located in 1982 and 1,029 located in 1983. Our purpose in this chapter is to describe an average spawning site in terms of apparent velocity and dissolved oxygen, if indeed such a generalization can be made.

Methods

Seepage meters were installed in transects perpendicular to shore at five sites during 1982 spawning and at eight sites during 1983 spawning (Woessner and Brick, 1983, 1985). At four sites, three to four meters were placed at the same elevation parallel to shore for the measurement of lateral variation in flux. During 1984 spawning, FWP scientists placed from 10 to 31 seepage meters in spawning areas adjacent to and directly over redds at eight sites. They also obtained similar seepage and DO data for one kokanee spawning site in Ashley Lake and Swan Lake. The 1984 data were all collected at a Flathead Lake stage of 2890 ft. That data base was augumented by the inclusion of seepage and DO data collected in previous years at the same lake stage.

We decided to lump the data and examine the means and central tendency of the distributions. Means and standard deviations were calculated for apparent velocity and dissolved oxygen data from all sites at all spawning elevations, at each site for all site elevations and at each elevation for all sites and finally for each elevation at each site. Spawning elevations used were whole number values between 2888 ft and 2869 ft. We also did linear regressions of a few subsets of data to see if there were any significant correlations.

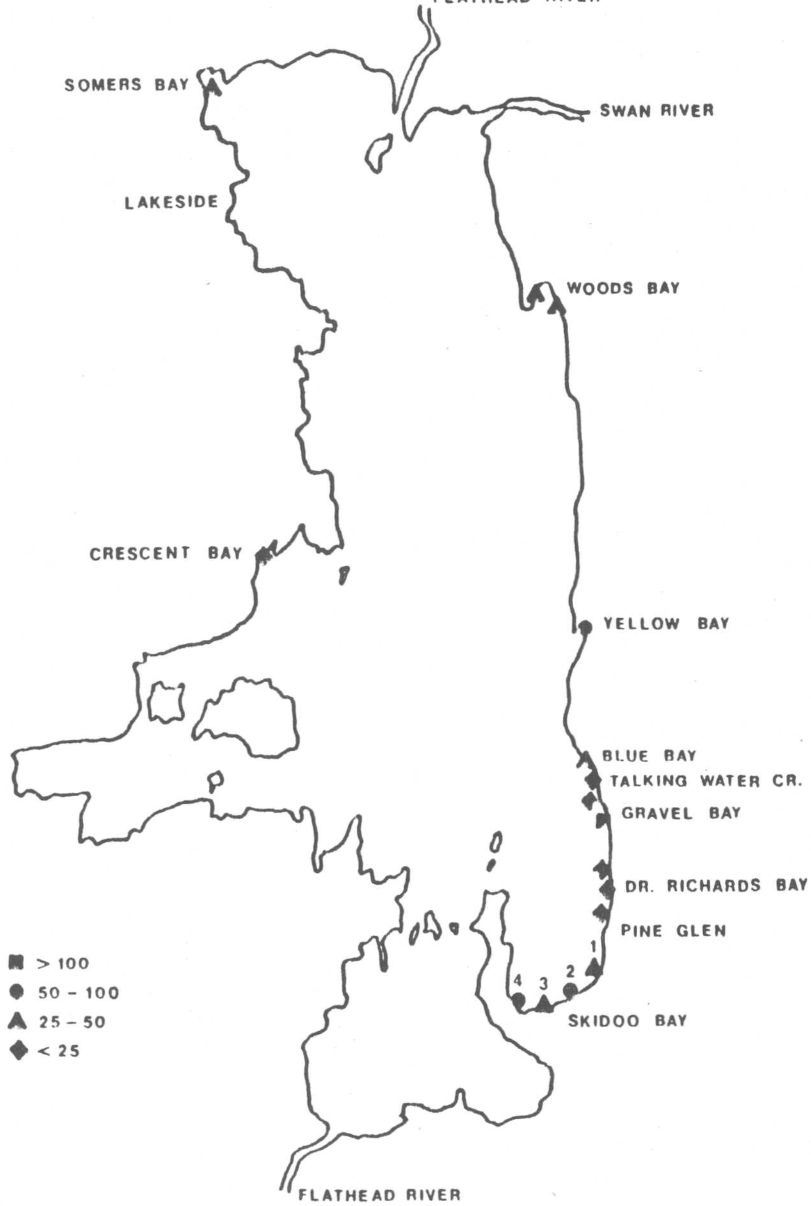


Figure 13 Location of shoreline spawning areas in Flathead Lake, 1983. Shape of symbol denotes number of redds in each area.(Decker-Hess and Clancy, 1984)

Results

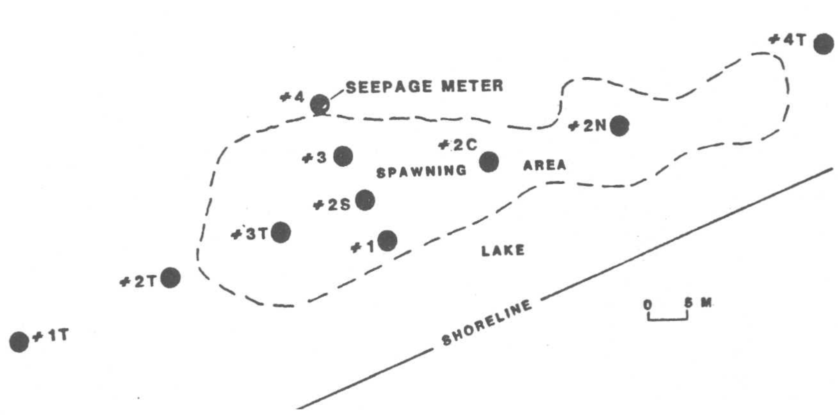
Our previous work revealed spatial and temporal variations in apparent velocity data (Figure 14 and 15). Theses data are examples of the variablity in ground-water discharge both parallel and perpendicular to shore which were described in the previous chapter. Profiles with changes in gradient and hetrogeneous geologic material are the rule instead of the exception. Base on two years of data collected at three to seven locations within a site during various lake stage elevations, 2891 to 2887 ft, mean apparent velocity and DO values were calulated for eight shoreline sites (Table 1). This analysis groups all the data at all elevations for two years at each site. Most meters were located in over three feet of water which is below active wave base. This eliminated the inclusion of high, near-shore seepage rates in the data base. Apparent velocity rates varied from 0.02 to 0.60 cm/hr and site means from 0.11 to 0.22 cm/hr. DO measurements reported by FWP personnel ranged from 1.0 to 12.1 mg/l and site means from 4.8 to 11.1 mg/l. The 1984 data were used to expand this initial data base by providing us with more statistically meaningful data.

It should be noted that DO values obtained from the seepage meters appear to be extremely high. Ground-water sampling by extracting samples directly from the sediments preformed by FWP divers consistantly showed lower values. Since the final compilation of the DO data that follows, we review pictures of the seepage meter collection bags taken during meter operation. Pockets of air were seen in the bags as they were attached to the submerged meters. We feel that if such was the normal operation mode of the seepage meters the DO data collected and summarized in this report is probably not representivity of the actual DO concentration in the ground water flowing through the redds. Though we have not changed the text, the DO results should be regarded as preliminary and needing independent experimental confirmation.

Using the entire data base, we first examined the variability of apparent velocity and DO at selected spawning elevation (Table 2). The largest standard deviations appear in the limited number of high elevation samples. Apparent velocity variability decreases with increasing sample numbers and generally with depth. DO values generally show more of a deviation at each site than apparent velocity data.

The second analysis evaluates the mean apparent velocity and DO at each spawning elevation for all sites (Figure 16 and Table 3). As theory predicted, the highest seepage velocities are located closest to shore. However, the apparent velocity remains in the 0.23 cm/hr range from 2885 to 2871 ft. This mean is less than the mean for all sites of 0.53 cm/hr. Note that the deep site values are basically the same as the deeper shallow site values. DO measurements show an inverse relationship to seepage at near shore elevations (Figure 16 and Table3). Values at deeper sites remain above the 8.8 mg/l over all mean.

The third analysis lumps all data from each site (Figure 17 and Table 4). The highest seepage means were obtained from shallow sites with meter data from high elevations. Mean rates ranged from 0.14 cm/hr at Gravel Bay(a deep site) to 1.42 cm/hr at a shallow site, Skidoo Bay #2 (Orange House). DO means were as low a 4.8 mg/l at the Big Arm shallow site and 10.1 mg/l at the Gravel Bay site (Figure 17 and Table 4). The mean apparent velocities associated with spawning at Swan and Ashley lakes are 0.16 and 1.08 cm/hr,



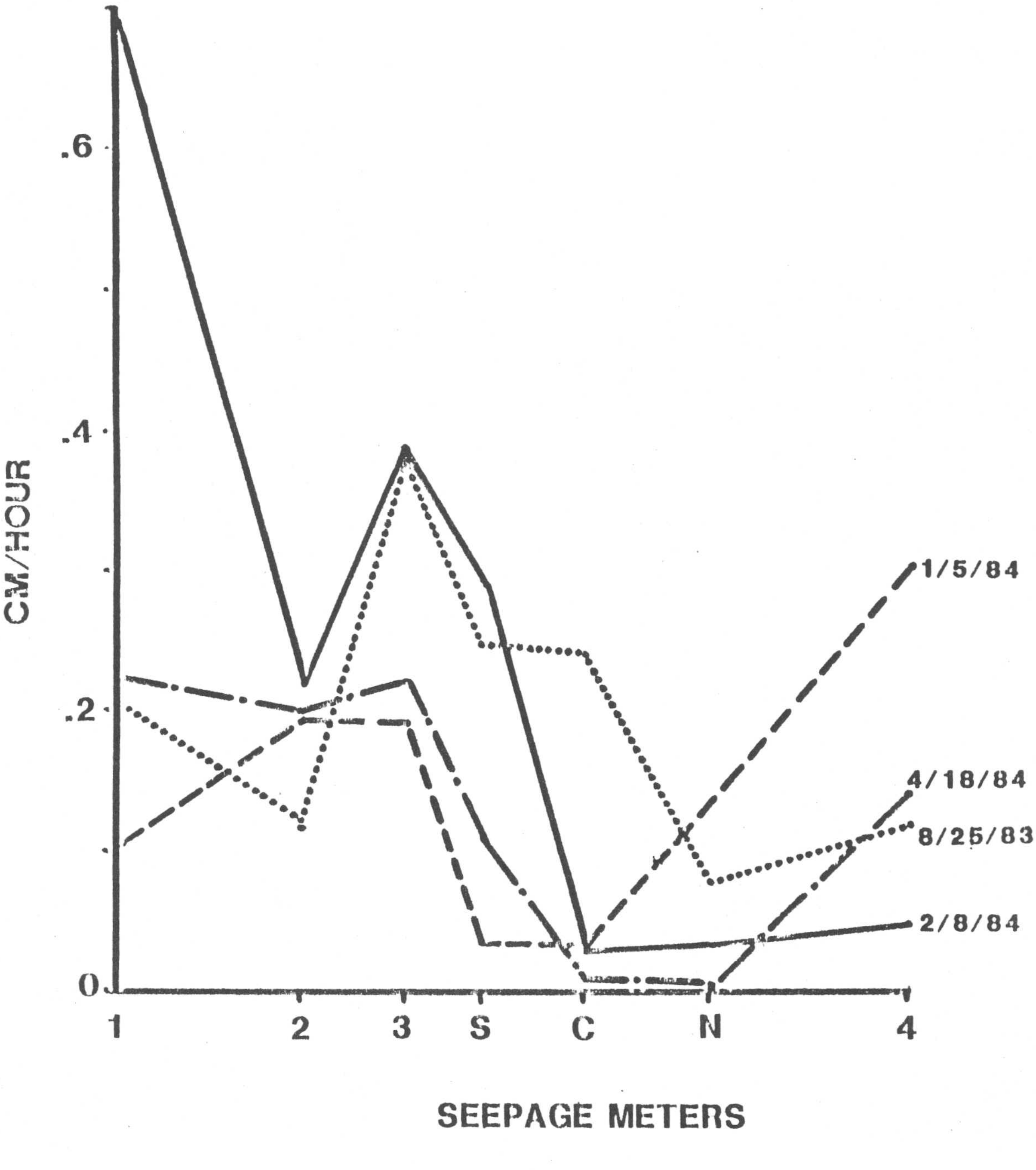


Figure 15: Seepage Variation Parallel to Shore
Gravel Bay

Table 1: Summary of hydrogeologic conditions during spawning (October through December).

	Apparent velocity (cm/m)			Water quality (mg/l) TDS			Cl			DO		
	Range	Mean	n	Range	Mean	n	Range	Mean	n	Range	Mean	n
Group I												
Dr. Richards S	-	-	-	-	-	-	-	-	-	-	-	-
Woods Bay West	-	-	-	-	-	-	-	-	-	8.1-10.4	9.6	6
Woods Bay East	-	-	-	-	-	-	-	-	-	9.4-11.4	10.6	6
Gravel Bay	0.05-0.37	0.18	19	137-275	206	2	0.20-0.28	0.24	2	1.0- 9.8	8.2	19
Gravel Bay Ex	-	-	-	-	-	-	-	-	-	-	-	-
Pine Glen	-	-	-	-	-	-	-	-	-	7.5-10.2	9.0	9
Somers	0.11-0.32	0.19	4	-	142	1	-	0.34	1	10.1-12.1 7.5-10.5	11.1 9.6	3 4
Group II												
Skidoo Bay	0.13-0.49	0.22	12	-	156	1	-	0.30	1	5.4-12.8	9.0	27
Orange House	-	-	-	-	-	-	-	-	-	-	-	-
Yellow Bay	0.02-0.38	0.22	10	136-279	173	5	0.20-0.69	0.32	5	0.3- 9.6	3.4	33
Group III												
Dr. Richards N Hochmarks	-	-	-	-	-	-	-	-	-	7.8-11.5	10.1	6
Gallagher	-	-	-	-	-	-	-	-	-	3.7- 6.4	4.8	6
W. Gallaghers	-	-	-	-	-	-	-	-	-	6.1-11.4	8.4	6
Crescent Bay	0.02-0.60	0.22	18	114-297	214	7	0.21-0.69	0.50	7	6.1-10.8	8.9	7
Others												
Deep Bay	0.05-0.17	0.11	2	144-147	146	2	0.21-0.25	0.23	2	7.4- 9.5	8.4	2
Table Bay	0.04-0.34	0.18	8	136-138	137	4	0.19-0.33	0.24	4	8.8-10.5	10.1	6
Woods Bay	0.02-0.51	0.23	15	-	-	-	-	-	-	9.3-11.5	10.2	11

TABLE 2: Mean (X), standard deviation (s) and number of samples (n) at a given spawning elevation by site. Units are elevation (ft), apparent velocity (v*) cm/hr and DO, mg/l.

	2888'						2887'						2886						2885					
	v*			DO			v*			DO			v*			DO			v*			DO		
SITE	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s
Pine Glen							1	2.25		1	10.2		5	1.79	3.10	5	9.9	0.19	4	0.23	0.15	4	10.1	0.25
Dr. Richards							1	0.51		1	10.0		2	0.33	0.17	2	9.8	0.35	3	0.25	0.06	3	10.3	0.15
Skidoo Bay							4	5.11	2.52	4	9.3	1.0	5	0.24	0.08	5	7.6	3.8	6	0.34	0.18	6	8.7	1.3
Thurstons	3	4.15	0.49	3	5.5	2.72	3	0.44	0.27	3	5.3	3.2	9	0.92	0.26	9	5.6	3.3	2	0.41	0.08	2	8.2	0.35
Gravel Bay																								
Woods Bay													6	2.07	1.51	6	8.1	1.85	9	0.30	0.16	10	9.5	0.86
Blue Bay																								
Big Arm							3	0.15	0.10	2	6.6	4.3	5	0.13	0.09	3	4.1	4.2	2	0.12	0.12	1	3.1	
Yellow Bay																								
Crescent Bay							4	0.11	0.10	1	6.1													

TABLE 2 cont.

SITE	2884'						2883'						2882						2881'					
	v*			DO			v*			DO			v*			DO			v*			DO		
	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s
Pine Glen	5	0.18	0.08	5	10.1	0.41	3	0.72	0.94	3	9.9	0.15												
Dr. Richards	4	0.28	0.03	4	10.1	0.53	4	0.19	0.10	4	8.3	3.3	2	0.23	0.02	2	8.3	3.0						
Skidoo Bay	3	0.20	0.0[illegible]	2	8.9	0.78																		
Thurstons	1	0.21		1	5.0																			
Gravel Bay							2	0.35	0.11	2	10.2	0.35	1	0.27		1	7.6							
Woods Bay	8	0.25	0.16	8	9.3	0.97	4	0.14	0.16	4	7.4	1.22	3	0.36	0.05	3	8.6	0.20						
Blue Bay																								
Big Arm																								
Yellow Bay							1	0.28											1	0.24				
Crescent Bay																								

TABLE 2 cont.

	2880'						2879'						2878'						2877'					
	v*			DO			v*			DO			v*			DO			v*			DO		
SITE	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s
Pine Glen																								
Dr. Richards																								
Skidoo Bay																								
Thurstons																								
Gravel Bay	4	0.15	0.09	3	10.3	1.1							2	0.26	0.06	2	9.9	0.57	4	0.15	0.05	4	10.3	0.39
Woods Bay																								
Blue Bay																			2	0.32	0.03	2	9.0	0.21
Big Arm																								
Yellow Bay																			2	0.26	0	1	8.2	
Crescent Bay																								

TABLE 2 cont.

	2876'						2875'						2874'						2873'					
	v*			DO			v*			DO			v*			DO			v*			DO		
SITE	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s
Pine Glen																								
Dr. Richards																								
Skidoo Bay																								
Thurstons																								
Gravel Bay	2	0.10	0.10	2	10.8	0.21	6	0.15	0.08	3	10.5	0.55	1	0.19		1	10.7		4	0.05	0.05	4	10.3	0.81
Woods Bay																								
Blue Bay	2	0.39	0	2	9.8	0.42	2	0.42	0.05	2	9.8	0.28	5	0.28	0.08	5	9.5	1.1						
Big Arm																								
Yellow Bay																								
Crescent Bay																								

TABLE 2 cont.

SITE	2872' v* n	X	s	DO n	X	s	2871' v* n	X	s	DO n	X	s	2870' v* n	X	s	DO n	X	s	2869' v* n	X	s	DO n	X	s
Pine Glen																								
Dr. Richards																								
Skidoo Bay																								
Thurstons																								
Gravel Bay	3	0.13	0.10	3	10.0	0.67	2	0.11	0.03	2	10.9	0.35							4	0.13	0.05	2	9.8	0.99
Woods Bay																								
Blue Bay	2	0.30	0.16	2	8.6	0.21	2	0.20	0.16	2	6.9	0.14							1	0.23		1	6.6	
Big Arm																								
Yellow Bay	2	0.10	0.11																					
Crescent Bay																								

TABLE 2 cont.

	2868'						2867'						2866'						2865'					
	v*			DO			v*			DO			v*			DO			v*			DO		
SITE	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s
Pine Glen																								
Dr. Richards																								
Skidoo Bay																								
Thurstons																								
Gravel Bay	1	0.18		1	11.4								1	0.22		1	10.2		1	0.12		1	10.4	
Woods Bay																								
Blue Bay																								
Big Arm																								
Yellow Bay							2	0.15	0.18	1	11.1													
Crescent Bay																								

TABLE 2 cont.

	2864'						2863'																	
	v*			DO			v*			DO			v*			DO			v*			DO		
SITE	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s	n	X	s
Pine Glen																								
Dr. Richards																								
Skidoo Bay																								
Thurstons																								
Gravel Bay							2	0.23	0.06	1	9.0													
Woods Bay																								
Blue Bay																								
Big Arm																								
Yellow Bay																								
Crescent Bay																								

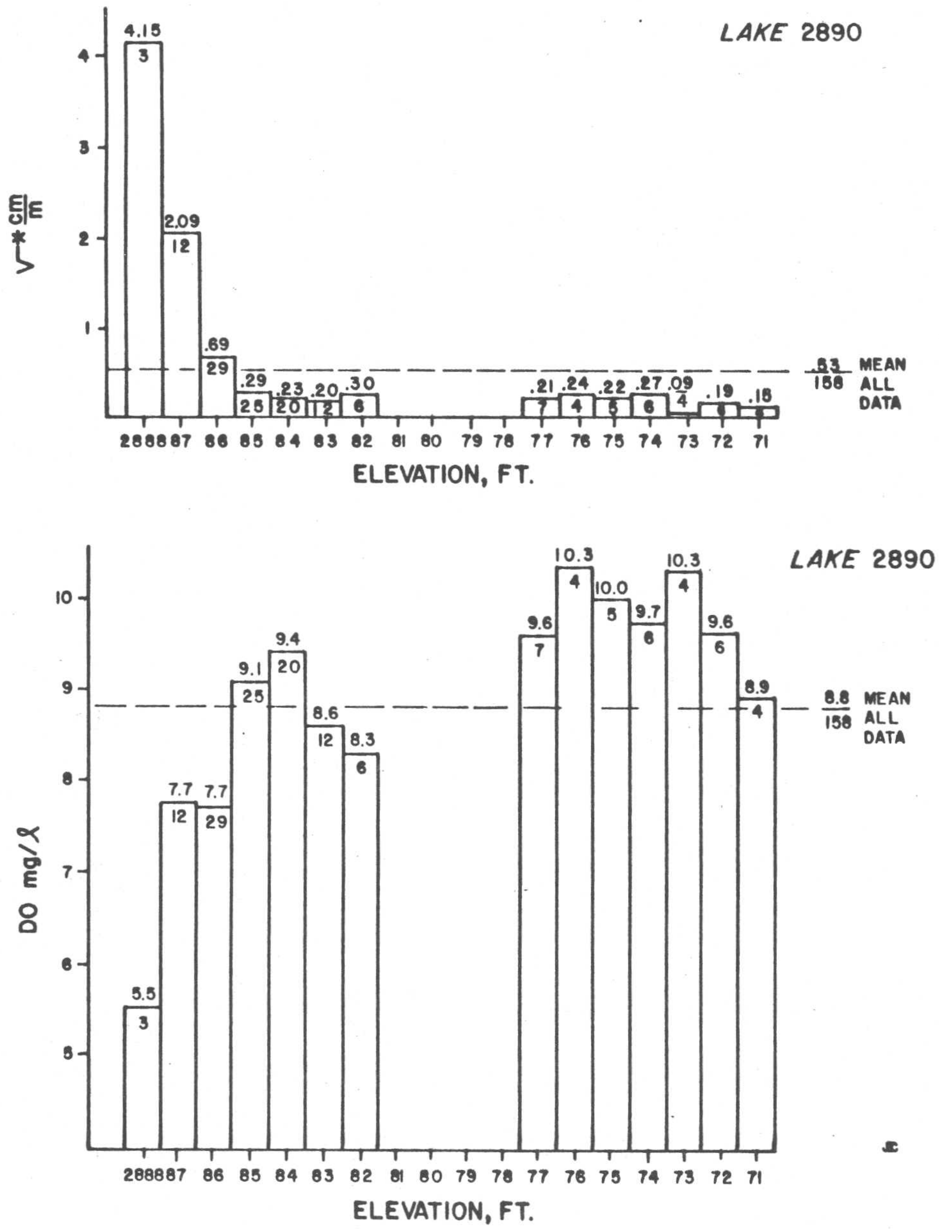


Figure 16: Mean apparent velocity and DO values for spawning elevations at all sites.

Table 3

ALL SITES AT A GIVEN ELEVATION

		DO mg/l		# of sites included
Elevation	n	$\overline{X}$	s	
2888	3	5.5	2.7	1
2887	12	7.7	2.8	6
2886	29	7.2	3.3	6
2885	25	9.1	1.6	6
2884	20	9.4	1.3	5
2883	12	8.6	2.2	4
2882	6	8.3	1.4	3
2877	9	9.6	.9	3
2876	4	10.3	.7	2
2875	5	10.0	.8	2
2874	6	9.7	1.1	2
2873	4	10.3	.81	1
2872	6	9.6	.85	3
2871	4	8.9	2.3	2

Table 3(cont)

ALL SITES AT A GIVEN ELEVATION

		v* cm/hr	
Elevation	n	$\overline{X}$	s
2888	3	4.15	.49
2887	12	2.09	2.65
2886	29	.69	.98
2885	25	.29	.16
2884	20	.23	.11
2883	12	.20	.14
2882	6	.30	.07
2877	7	.21	.09
2876	4	.24	.19
2875	5	.22	.19
2874	6	.27	.08
2873	4	.05	.05
2872	6	.19	.13
2871	4	.15	.11

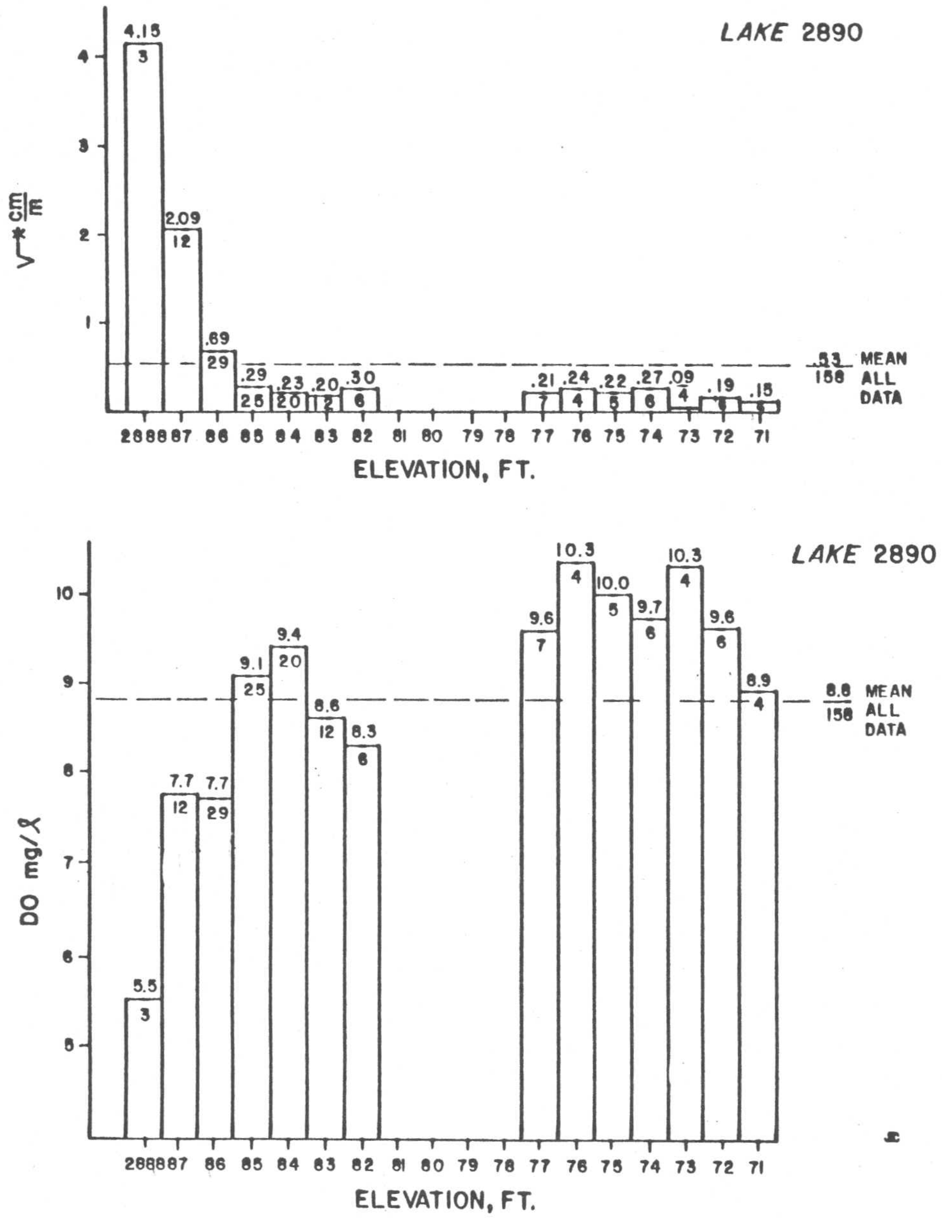


Figure 17: Mean apparent velocity and DO values for all elevations at each site.

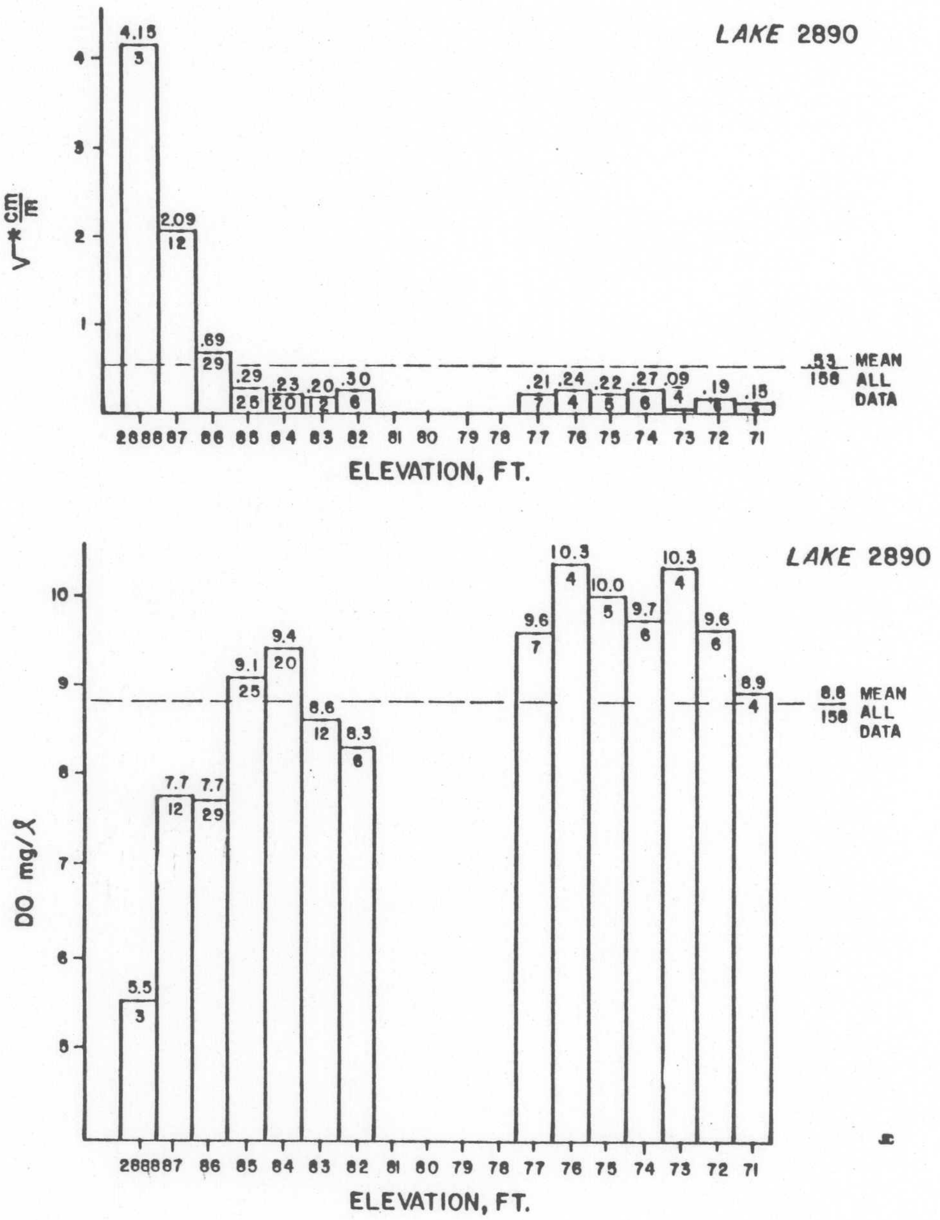


Figure 17: Mean apparent velocity and DO values for all elevations at each site.

Table 4

ALL ELEVATIONS AT EACH SITE (LAKE = 2890)

	v*			DO		
Site	n	$\overline{X}$	s	n	$\overline{X}$	s
Gravel Bay	34	.15	.09	34	10.1	1.1
Dr. Richards	16	.27	.11	16	9.4	1.9
Pine Glen	17	.87	1.77	17	9.5	2.3
Skiddoo Bay	17	1.42	2.38	17	8.5	2.2
Thurston´s	18	1.03	1.46	18	5.8	2.9
Blue Bay	16	.31	.10	16	8.9	1.3
Big Arm	10	.14	.09	6	4.8	3.6
Woods Bay	31	.60	.97	31	8.5	2.0
Yellow Bay	8	.19	.11	3	8.5	2.0
Crescent Bay	8	.18	.19	2	8.3	3.1
ALL ELEVATION AT ALL SITES	158	.53	1.08	158	8.8	2.3
Other Sites						
Swan Lake	15	.16	.06	15	8.9	.93
Ashley Lake	17	.96	1.08	17	7.8	1.25

respectively. DO means for the sites are 8.9 mg/l at Swan Lake and 7.8 mg/l at the Ashley Lake site.

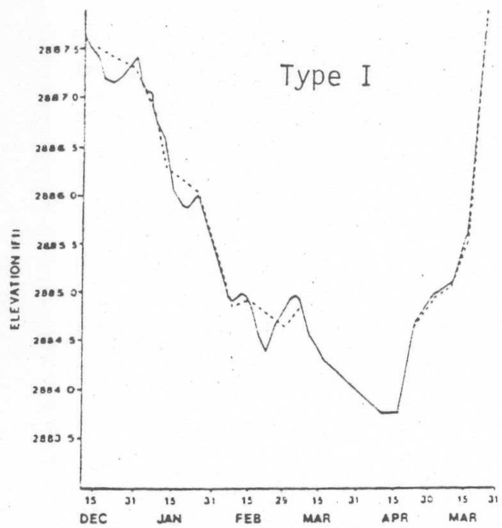
The mean of apparent velocity for all elevations at all sites is 0.53 cm/hr. The mean DO for all elevation at all sites is 8.8 mg/l. The standard deviations are 1.08 cm/hr and 2.3 mg/l, respectively.

Examination of the data for linear relationships met with mixed success. Correlation of mean velocity with elevation at all sites yielded a correlation coefficient of 0.59 for all elevations, 0.48 for the 2877 to 2871 ft interval and 0.82 for the 2888 to 2882 ft interval. Evaluation of mean DO with elevation at all sites resulted in a correlation coefficient of -0.74 for all elevations, 0.50 for the 2877 to 2871 ft interval and -0.52 for the 2888 to 2882 ft interval. Mean apparent velocity correlation with mean DO for all sites for a given elevation interval yielded a correlation coefficient of -0.84 for the 2888 to 2871 ft interval, -0.07 for the 2877 to 2871 ft interval and -0.87 for the 2888 to 2882 ft interval.

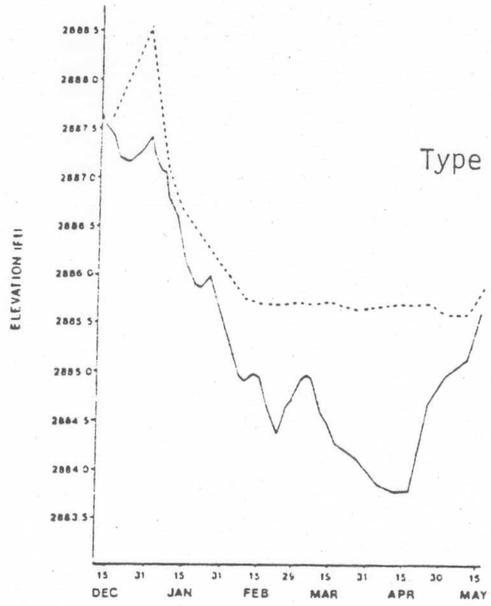
Discussion

We feel that a characterization of the hydrogeology of the generic Flathead Lake kokanee spawning site is best accomplished by examinating the apparent velocity and DO data by elevation. The high seepage rates near shore, between 2888 and 2886 ft, are anticipated by ground-water flow theory. However from 2885 to 2871 ft, the rates generally remain in the 0.30 to 0.15 cm/hr range. Favorable spawning sites appear to have beach profiles and ground-water systems which maintain this range of seepage. At deeper depths the accumulation of fine sediments reduces both seepage and oxygen. The mean apparent velocity value is weighted by measurements between 2888 ft and 2886 ft. It overestimates the values for deeper sites. The DO values are lowest in the sites nearest to shore and highest in the deepest sites with some decrease at 2872 to 2871 ft. The over all mean value of DO is generally too high to represent the shallow site conditions and too low to represent the deeper sites. DO data should be reguarded as preliminary.

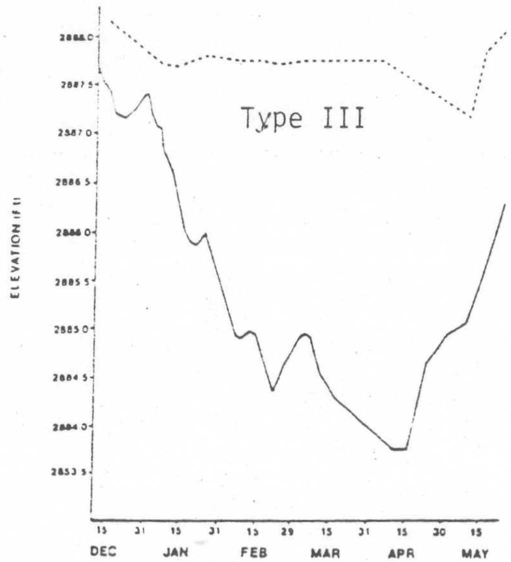
The "typical" shallow spawning sites close to shore will have the highest apparent velocities and lowest DO. Sites located between 2885 and 2882 ft will have a narrow range of mean values, 0.20 to 0.30 cm/hr for apparent velocity and 8.3 to 9.1 mg/l for DO. Spawning at deeper elevations ocurs under similar hydrgeologic conditions, a range of mean seepage velocities of 0.05 to 0.27 cm/hr and DO means ranging from 8.9 to 10.3 mg/l. These characteristics also correspond to the mean values calculated for transects of a few meters usually located below wave base, thus excluding the higher near-shore seepage values and lower DO values associated with the higher spawning elevations (Table 1). The concentration of total dissolved of the calcium carbonate dominated seepage ranged from 114 to 297 mg/l (Table 1). Chemical differences appear to be more geologically related than tied to apparent velocity conditions. The high DO values measured in the seepage water are apparently not unusual values for the glacial sediments and associated bedrock aquifers discharging to the lake. Typically in areas with a thicker weathering zone, organic material in the soil zone reacts with dissolved oxygen in infiltrating water and depletes the recharge water. The absence of



Comparison of lake level fluctuations (solid line) and water table fluctuations (dotted line) at … Bay West, an example of type … groundwater areas. Stars denote the period of time that the well was dry.



Comparison of lake level fluctuations (solid line) and water table fluctuations (dotted line) at Yellow Bay, an example of type 2 groundwater areas.



Comparison of lake level fluctuations (solid line) and water table fluctuations (dotted line) at Dr. Richard's Bay North, an example of type 3 groundwater areas.

Figure 18: Comparison of Lake Stage with water table response (after Decker-Hess and Clancey,1984).

local ground-water system and the discharge of a more regional flow systems may provide the required recharge.

The number of redds located in shallow 1983 Type I to Type III sites is presented in Table 5. The highest kokanee survival rate, 72%, was recorded in Type III shallow sites and the lowest rate in Type I sites (Decker-Hess and Clancy, 1984). Type II areas had between 24 and 65 % survival.

Because of the possiblity that previous operating scenarios may have created different periods of redd exposure without ground-water flow, we were asked to predict the timing and period of exposure resulting from historical dam operation. Decker-Hess and Clancy (1984) identified five major operating scenarios from 1940 to the present (Figure 19) and Beatty (person. comm., 1985) identified the ten year period from 1960 to 1970 as possibly a critical time to be assessed. We employed numerical modeling to predict the historical impact on redd exposure time.

Methods:

Predictive modeling was limited to Site 1 at Skidoo Bay, a Type II water table response site. Numerical modeling of Type I or Type III responses to the requested scenarios was deemed unnecessary. Both Type I and Type III sites have easily predictable responses to lake stage change. We believe the poor survival rates seen in Type I sites today would also have been poor under the other operating schedules. Conversely, the high survival rates observed at Type III sites would remain high during the tested schedules. The behavior at Type II sites is much less predictable, requiring a more sophicated approach. Because we had two years of data at the Type II Skidoo I or Staples Site it was selected for modeling. Chris Brick developed, calibrated and excuted the hydrogeologic model of the Skidoo Bay site. A brief description of the model and its application follows.

The model used in the simulation of the water table response to various lake stage operation scenarios is documented by Prickett and Lonnguist (1971) and Prickett et al. (1981). The finite difference model was used to simulate two dimensional water table flow in map view. In the model, the continuous field is discretized into a finite number of blocks in a grid and enclosed by defined hydrogeologic boundary conditions (Figure 20). The north and south boundaries are parallel to ground-water flow and are defined as no- flow boundaries. The east boundary is a constant head boundary based on field measurements of water levels in a domestic well. The west boundary is also a constant head boundary and represents the elevation of Flathead Lake. The model was modified to allow the west boundary to move and change elevation at five day intervals corresponding to lake stage changes recorded at Kerr Dam. Values for water table elevation, hydraulic conductivity, aquifer thickness and aquifer storage were entered at all nodes. Values from actual field measurements were extrapolated to all the nodes. Figure 20 lists default parameters and zone parameters used in the modeling. Model code and an example of the data set required are part of the appendix of Chris Brick's Master of Science in Environmental Sciences which will be available in the winter of 1986.

The model was calibrated to steady state and then unsteady flow conditions by using September 1983 data and April 1984 data. During the

Table 5: Categories of groundwater reaction to lake stage fluctuation at shoreline spawning areas and the number of redds above 2884.0 ft at each of those areas.(after Decker-Hess and Clancey, 1984)

Type I	Woods Bay West	35
	Woods Bay East	30
	Dr. Richard's Bay South	16
	Somers Bay	27
		108
Type II	Skidoo Bay I (East)	43
	Skidoo Bay II (West)	66
		109
Type III	Dr. Richard's Bay North	23
	Skidoo Bay III	41
	Skidoo Bay IV	50
	Crescent Bay	23
		137

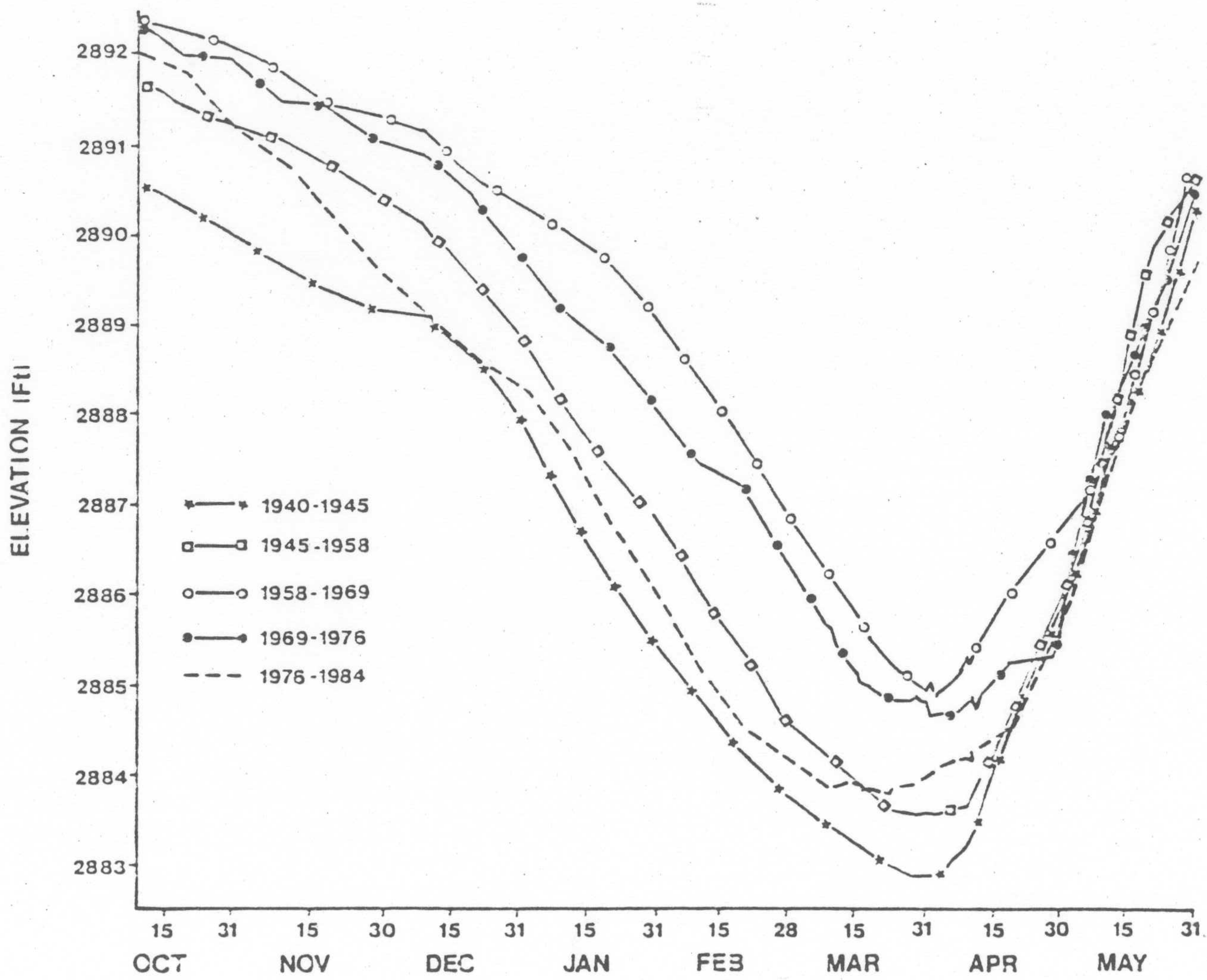


Figure 19. Mean hydrographs for 15 October through 31 May for Flathead Lake for grouped years of 1940-45, 1945-58, 1958-69, 1969-76 and 1976-84. (after Decker-Hess and Clancey, 1984)

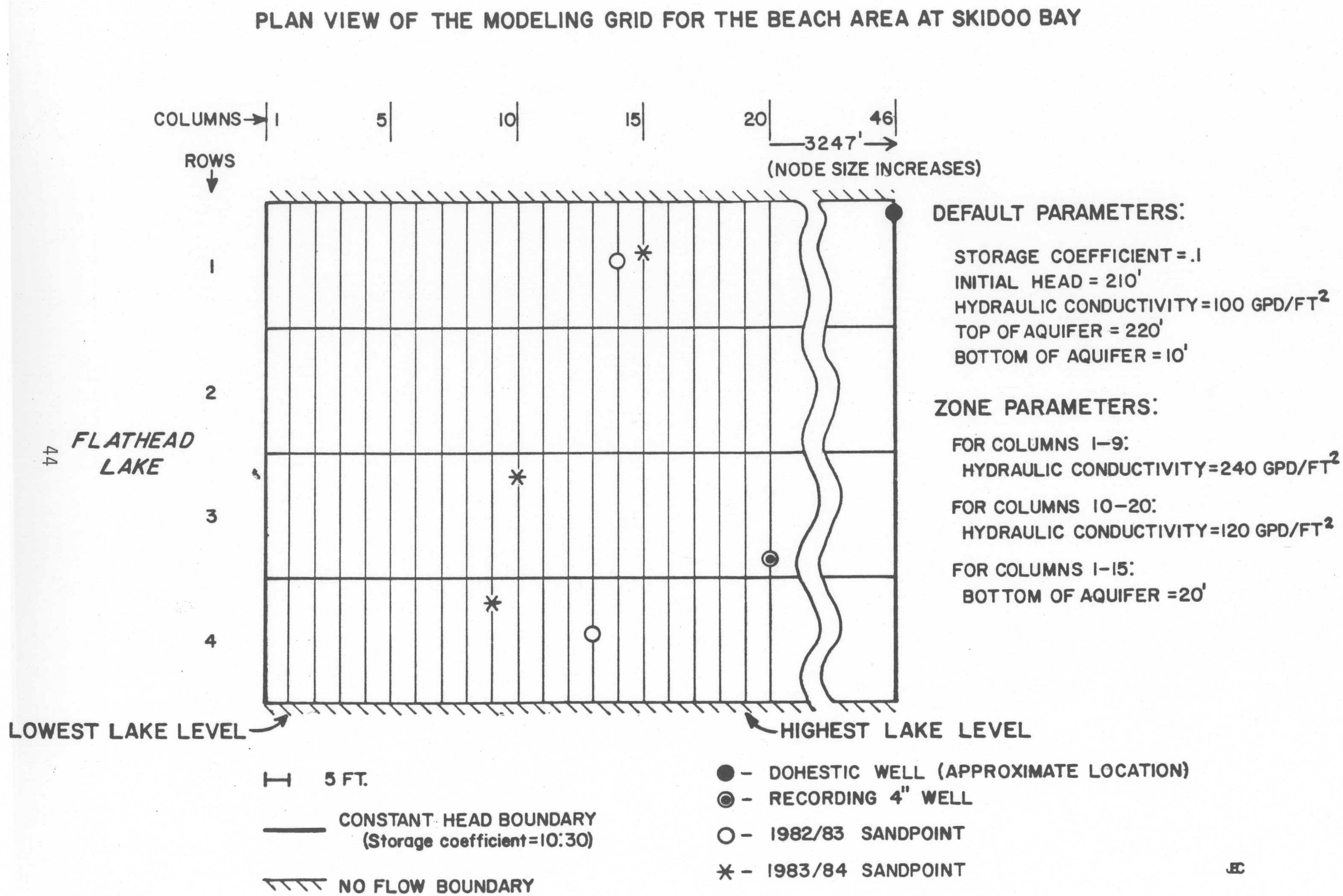


Figure 20: Plan view of the modeling grid for the beach area at Skidoo Bay.

calibration procedure aquifer thickness and hydraulic conductivity values were adjusted to obtain the steady state and transient distribution of heads measured at the recording well and sandpoints. The final values of hydraulic conductivity used were 17 cm/hr for the aquifer west of the beach area and between 20 to 40 cm/hr for the beach sediments. The model was then verified with 1982 to 1983 and 1983 to 1984 sandpoint head data and recording well records (Figure 21 and 22). As can be seen from the two figures, the water table hydrographs produced by the model form the same shape as the actual well hydrographs. Predicted water table elevations are within 3.6 inches of measured water level elevations. Given the complexity of the area, we consider the model results to be a good match to the real data. After the verification process, we ran the five historic scenarios through the model and predicted the water table position for each one at five day intervals. The simmulation modeling assumes that the existing beach profile is representative of the historic beach profile.

Results

The results of the five operation schemes are presented in Table 6. The redds below 2884.75 ft were continually bathed in ground water during each of the five periods. Redds at the 2885.65 ft, 2886.80 ft and 2887.40 ft elevations were positioned above the water table for the longest period in 1940 to 1945. Similar periods of exposure occured again in the period from 1976 to 1983. Redds remained wetted for the longest period of time during 1958 to 1968, thus this period appears to be the most favorable for embryo and fry survival.

The results of the yearly evaluation of the period 1960 to 1970 is presented in Table 7. As seen with the analyses of the five groups above, the spawning sites below 2884.75 ft were continuously bathed with ground-water flow during this ten year span. The three higher spawning elevations showed the longest periods of exposure from ground water. The periods corresponding to the longer intervals without ground-water flow at redd level are seen in 1961 to 1962, 1965 to 1966, 1966 to 1967 and 1969 to 1970. In 1960 to 1961 all spawning elevations were continually receiving ground-water flow.

Discussion

The model results indicate that ground-water flow is significant for redds below 2884.75 ft at Skidoo Bay. Above this elevation the water table falls below the base of redds for various lengths of time. The variation in the peroid of exposure from ground water relates to the rate of rise and fall of the lake stage, stage highs and lows, and the beach profile at the site. The greatest periods of exposure occurred in years with the lowest lake position at the start of spawning and during incubation. The beach profile at the Skidoo site also effects the ground-water discharge patterns. The slope is 4% to a depth of 2884.75 ft but in the next five feet beyond, the slope is 18%. The steeper slope marks the lower edge of the wave-sorted gravel and the upper edge of the lake bottom sand. The break in slope, and the higher hydraulic conductivity of the beach gravel, results in a lower water table upshore of the break. The water table falls below redd depth once the lake stage has dropped past the redd elevation. The steepening of the slope and lowering of the hydraulic conductivity at and below the slope break results in

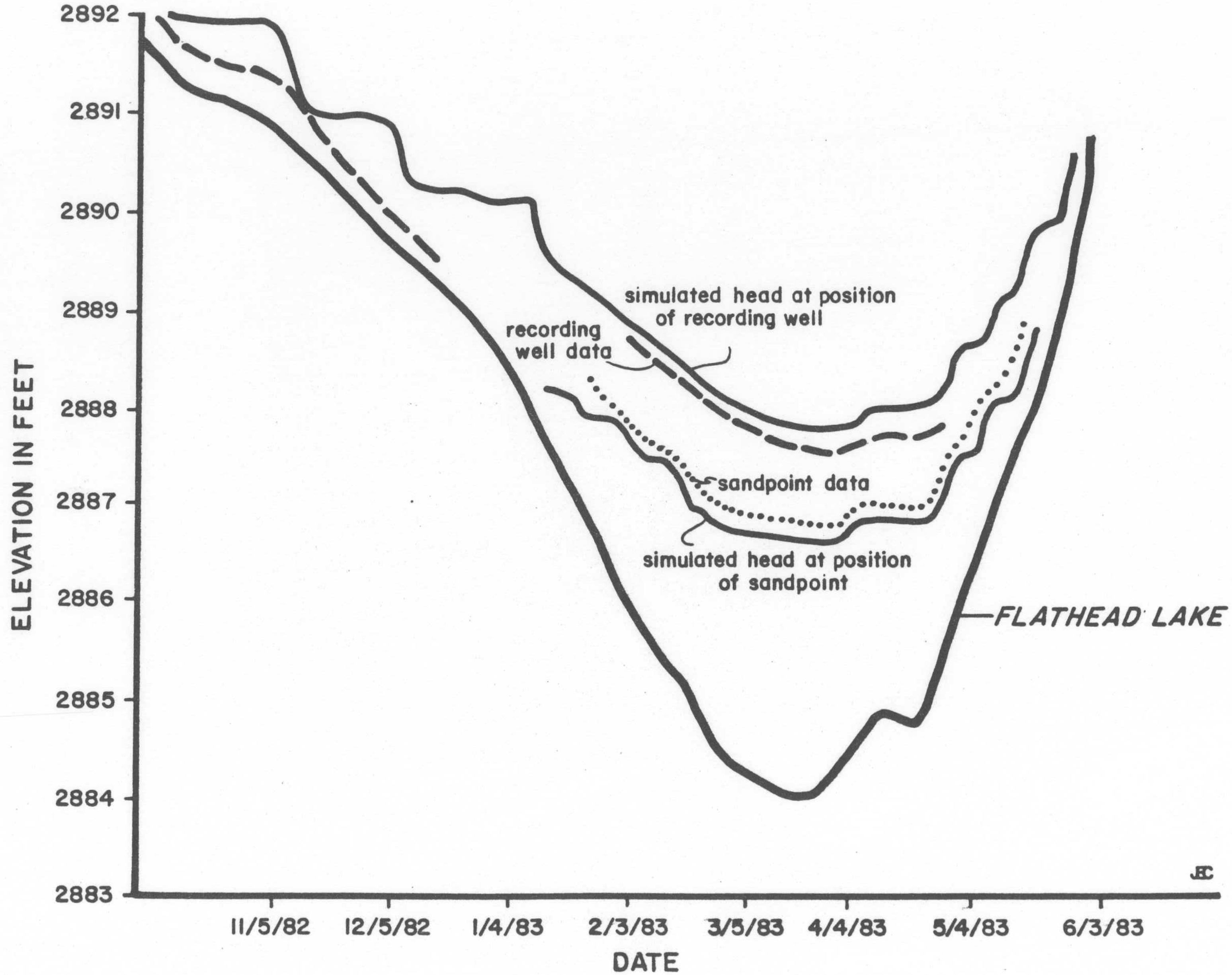


Figure 21: Model calibration , 1982-1983 data.

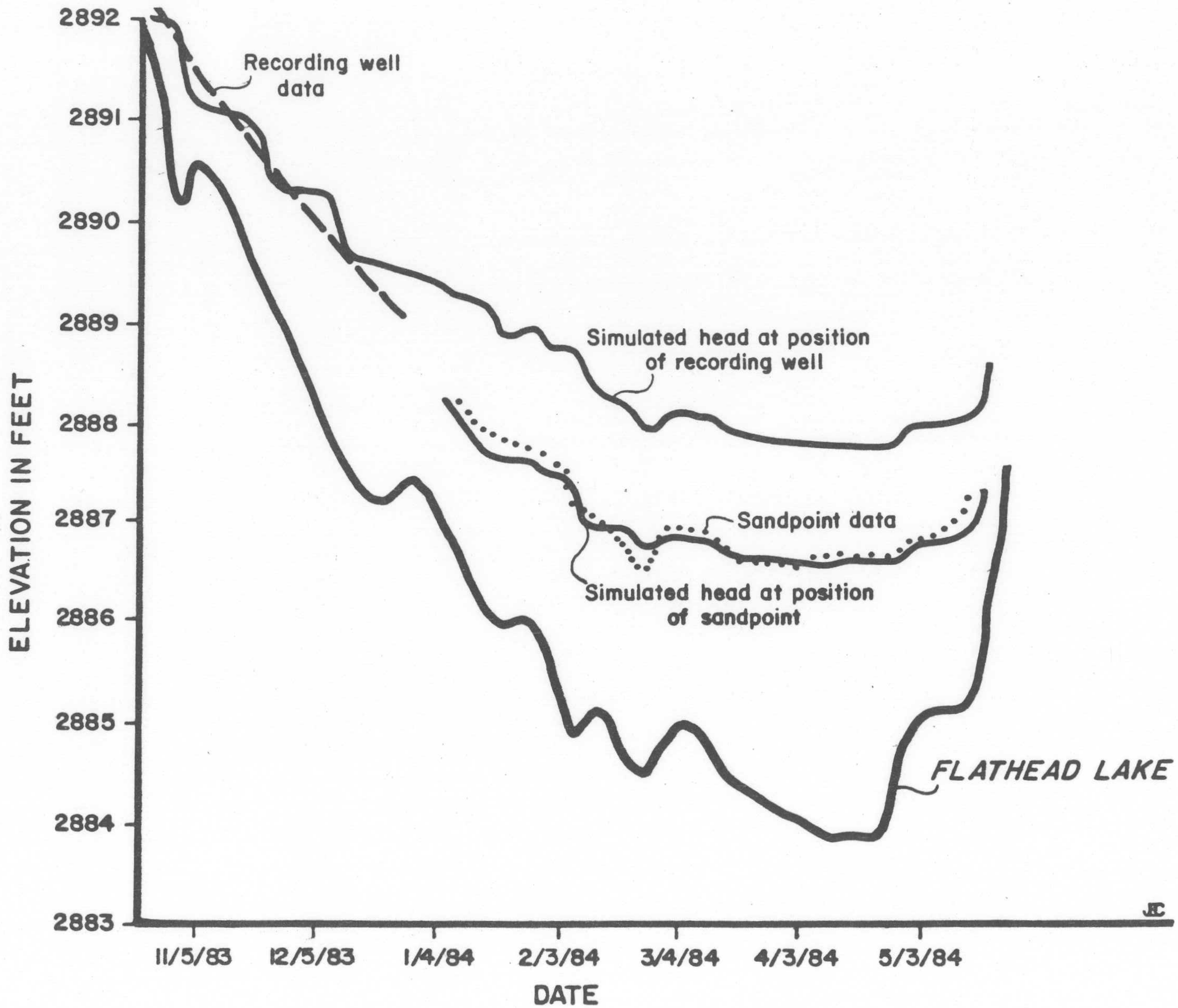


Figure 22: Model calibration, 1983-1984 data.

TABLE 6: Modeling results, periods of exposure for grouped years.

YEARS	BEACH ELEV.	DAYS EXPOSED FROM LAKE	ACTUAL DATES	DAYS EXPOSED FROM GROUNDWATER (>15cm below beach surface)	DATES
1940	83	5	3/29-4/03	0	-
	84	45	3/04-4/18	0	-
to	84.75	66	2/17-4/23	0	-
	85.65	81	2/07-4/28	81	2/07-4/28
1945	86.80	111	1/18-5/08	81	2/07-4/28
	87.40	121	1/13-5/13	100	1/29-5/08
	83	0	-	0	-
1945	84	25	3/24-4/18	0	-
	84.75	45	3/09-4/23	0	-
to	85.65	61	2/27-4/28	61	2/27-4/28
	86.80	91	2/07-5/08	61	2/27-4/28
1957	87.40	106	1/28-5/13	86	2/12-5/08
	83	0	-	0	-
1958	84	0	-	0	-
	84.75	0	-	0	-
to	85.65	15	3/29-4/13	15	3/29-4/13
	86.80	50	3/09-4/28	15	3/29-4/13
1968	87.40	76	2/27-5/13	50	3/29-4/28
	83	0	-	0	-
1969	84	0	-	0	-
	84.75	0	-	0	-
to	85.65	30	3/19-4/18	30	3/19-4/18
	86.80	71	2/27-5/08	30	3/19-4/18
1975	87.40	86	2/27-5/13	60	3/09-5/08
	83	0	-	0	-
1976	84	0	-	0	-
	84.75	51	2/21-4/13	0	-
to	85.65	76	2/12-4/28	76	2/12-4/28
	86.80	91	1/28-4/28	76	2/12-4/28
1983	87.40	>96	1/23-(4/28)	>86	2/02-(4/28)

TABLE 7: Modeling results, periods of exposure for individual years, 1960-1970.

	ELEV.	DAYS EXPOSED FROM LAKE	DATES	DAYS EXPOSED FROM GROUNDWATER	DATES
1960-61	83	0	-	0	-
	84	0	-	0	-
	84.75	0	-	0	-
	85.65	0	-	0	-
	86.80	0	-	0	-
	87.40	60	2/2-2/27, 3/9-4/13	0	-
1961-62	83	0	-	0	-
	84	15	3/29-4/13	0	-
	84.75	41	3/14-4/23	0	-
	85.65	55	3/04-4/28	55	2/27-4/28
	86.80	71	2/22-5/03	55	2/27-4/28
	87.40	86	2/17-5/03	66	2/12-5/08
1962-63	83	0	-	0	-
	84	0	-	0	-
	84.75	0	-	0	-
	85.65	0	-	0	-
	86.80	10	4/28-5/08	0	-
	87.40	77	3/14-5/23	5	5/03-5/08
1963-64	83	0	-	0	-
	84	0	-	0	-
	84.75	35	4/03-5/08	0	-
	85.65	40	4/03-5/13	40	4/03-5/13
	86.80	60	3/24-5/23	40	4/03-5/13
	87.40	70	3/14-5/23	55	3/29-5/23
1964-65	83	0	-	0	-
	84	0	-	0	-
	84.75	0	-	0	-
	85.65	10	4/13-4/23	10	4/13-4/23
	86.80	25	4/08-5/03	5	4/18-4/23
	87.40	35	4/03-5/08	25	4/08-5/03

Table 7 cont.

	ELEV.	DAYS EXPOSED FROM LAKE	DATES	DAYS EXPOSED FROM GROUNDWATER	DATES
	83	0	-	0	-
	84	10	4/08-4/18	0	-
1965-66	84.75	30	3/24-4/23	0	-
	85.65	55	3/19-5/13	55	3/19-5/13
	86.80	65	3/09-5/18	55	3/19-5/13
	87.40	75	3/04-5/18	65	3/14-5/18
	83	0	-	0	-
	84	0	-	0	-
1966-67	84.75	15	4/08-4/23	0	-
	85.65	50	3/29-5/18	50	3/29-5/18
	86.80	80	3/09-5/28	50	3/29-5/18
	87.40	85	3/04-5/23	75	3/14-5/28
	83	0	-	0	-
	84	0	-	0	-
1967-68	84.75	15	4/28-5/13	0	-
	85.65	30	4/18-5/18	30	4/18-5/18
	86.80	65	3/24-5/28	30	4/18-5/18
	87.40	>70	3/29->5/28	60	3/29-5/28
	83	0	-	0	-
	84	0	-	0	-
1968-69	84.75	0	-	0	-
	85.65	10	4/03-4/13	10	4/03-4/13
	86.80	40	3/14-4/23	10	4/03-4/13
	87.40	66	2/22-4/28	30	3/24-4/23
	83	0	-	0	-
	84	0	-	0	-
1969-70	84.75	45	3/29-5/13	0	-
	85.65	55	3/29-5/13	55	3/19-5/13
	86.80	91	2/17-5/18	55	3/19-5/13
	87.40	106	2/07-5/23	75	3/04-5/18

a seepage face at the break in slope. The beach below 2884.75 ft remains saturated to redd depth or becomes a site of seepage as the water table remains close to or at the beach surface. The configuration of the profile and the distribution of hydraulic conductivity appear to have important control on the position of the water table.

In our attempt to model the historic lake scenarios, we assumed that the lake profile did not change significantly over time. This is clearly an oversimplification (see Chapter IV). A different slope profile would result in a new set of water table elevations. A constant and gradual shoreline slope would result in more of the beach area being wetted by ground water. The model accurately predicts water table elevations under the present situation but the slope profile is a determinate variable which isn't accurately known for historic scenarios. However, accurate historic profiles are unavailable.

The results of our modeling effort are site specific. The model utilized requires specific data for the slope of the beach profile, the magnitude and spatial distribution of the hydraulic conductivity, the depth to an impermeable layer, an upshore value of head to use for the recharge boundary, and sandpoint head data from the spawning area to use for calibration and verification of the model. However, the response of the water table to various dam operation scenarios would be similar at other sites with like geology and beach profiles. Hydrogeologic conditions observed in the field at the Type II ground-water response Skidoo Bay site are similar to those at recorded at other Type II sites. We believe that calculated lengths of exposure times would probably be proportional. However, without specific modeling of each site further predictions cannot be made.

Additional modeling efforts should focus on determining the effect of various beach profile configurations on exposure duration at Skidoo Bay. Sensitivity analyses should be completed.

CHAPTER IV

MODIFICATION OF SHORELINES ON FLATHEAD LAKE RESULTING FROM ARTIFICIALLY RAISED LAKE LEVELS

PREFACE

The first section describes the modifications of the shoreline of Flathead Lake at several specific localities, and what are believed to be the primary causes of these modifications. To understand these changes the reader must have a fundamental understanding of wave processes. To establish a common ground of understanding, a brief introduction on the processes of wave erosion and sediment transport by waves is included. Specifically, in this section Dr. Moore attempts to relate the ideas of wave dynamics to the situation at Flathead Lake. The interpretations of shoreline modification at several stretches of shoreline with emphasis on amount of change and general morphologic transformations are described.

In all such discussions it is important for the reader to understand the limitations of interpretations of historical change. To precisely characterize the changes in such a complex system as Flathead Lake one must have an original data base from which to measure change. Fortunately, aerial photographs that span 50 years are available for parts of the Flathead Lake shoreline. The first of these photos was taken before the construction of Kerr Dam and establishes a baseline for measuring change since the lake levels were modified by the dam. The limitations of using aerial photographs result from the scale and coverage over time and space. Aerial photographs from 1934, 1935, 1937, 1954, 1955, 1966, 1972, and 1981 were used to make comparisons of the overall shoreline configuration. The shoreline and beach boundaries for each year were examined to identify sites of erosion and deposition. The shoreline was defined as the point where permanent vegetation existed and photographs taken at times of similar lake levels were used, when possible, to minimize water-level effects. In some cases, amounts of shoreline retrogradation or progradation were measured from "datum points" such as roads, field boundaries or some other development that could be seen not to change over the years. Variables such as scale of the photographs, flight angle and resolution limit the accuracy for such measurements. Aerial photographic methods are also limited to rather large features and many changes of a small magnitude would be undetectable using aerial photographs of the scale available for this work.

INTRODUCTION

When waves are generated by storms in the open ocean or large lakes, like Flathead Lake, they move away from the storm center and travel unrestricted as deep water swells. These swells can travel without significant decrease in energy as long as they remain in deep water because they have no effect on the bottom over which they pass. Deep water swells have a broad sinusoidal shape (Figure 23) but as they move into shallow water, the waves steepen and become peaked until they oversteepen and break. The waves start their transformation from the deep water forms to breaking waves when they enter water that is approximately half their wavelength in depth (Figure 24). Shoaling flattens

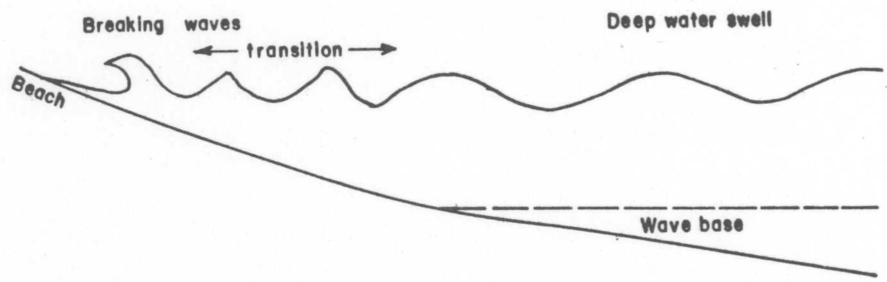


Figure 23: **SHAPES OF WAVES**

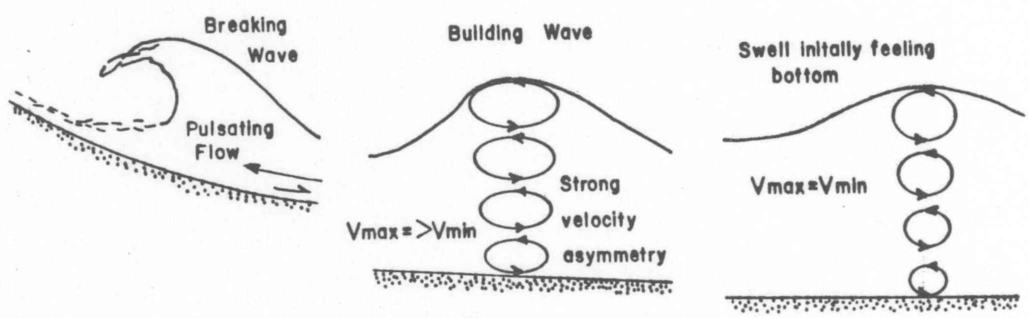


Figure 24: Wave mechanics.

the circular orbits of the water particles as the wave builds in height. When the wave height reaches approximately 80% of the water depth, the wave breaks, spilling water shoreward, transferring energy to the shore.

The width of the zone that receives this energy, the breaker zone, depends on the height of the waves and the steepness of the beach. If the beach is very steep and the wave can move relatively far shoreward before it starts to build, the breaker zone will be quite narrow (Figure 25A). In this case the beach receives most of the energy of the breaking waves in a very narrow zone. If the beach has a gentle slope, the waves interact with the bottom far from shore and the breaker zone is spread out over a rather broad area, dispersing the wave energy. On marine shorelines the wave dynamics often change from one of these to the other during the tidal cycle, as the sea level changes. In a lake like Flathead Lake, where the lake level remains constant over long periods, such changes will occur over months instead of hours. The important difference between these two situations is that when the wave energy is concentrated in a narrow zone, the beach tends to erode and material is transported lakeward (or oceanward) and deposited as a bar (Figure 26). Generally, this sediment is somewhat finer grained than the beach and if the waves are relatively small, a bar does not form. The sediment on the beach proper (plunge zone, Figure 26) is relatively coarse grained because the maximum wave energy is concentrated there.

These same changes will occur as the wave height and length change. Wave shape depends on the wind velocity, duration of wind and distance the waves travel from their site of origin. If short and high waves approach the shore (for example, those created in a nearby storm), they can travel well onto the beach before they break because of their short wavelength. Because they are also quite high, they transfer more water onto the beach and therefore cause erosion. Whereas with long wavelength, relatively low waves will break gently on the shore and cause no erosion. In fact, they may move sediment onto the beach from offshore bars. The beach profile responds to these different wave situations and becomes either steeper or gentler. Such processes very likely have occurred on Flathead Lake due to the modification in lake level since construction of Kerr Dam in 1938.

Hydrographs of the lake levels previous to construction of the dam show that the lake remained low during most of the year (Figure 27). It rose to a maximum elevation in May or June in response to spring runoff and then immediately fell to an elevation 8 to 10 ft lower, where it remained with only minor fluctuations during the late summer, fall and winter. Since the lake level has been maintained at a higher level, the hydrographs show a very different pattern (Figure 27). The lake remains at high elevations throughout most of the year and only drops to the previous lows during a short time immediately before spring runoff. This creates very different wave dynamics in the lake.

Previous to the construction of Kerr Dam, the shoreline would have reached an equilibrium with the wave dynamics of natural lake levels. The lake level would have been at low levels during most of the year, especially during times of strong fall and winter storms. A broad, coarse-grained beach would have formed over the entire area of the elevation range and the vegetated shoreline remained relatively stable somewhat above the high water line (Figure 28). Only very large storms, during the short time the lake was at high elevations, would have been able to signficantly erode the shoreline.

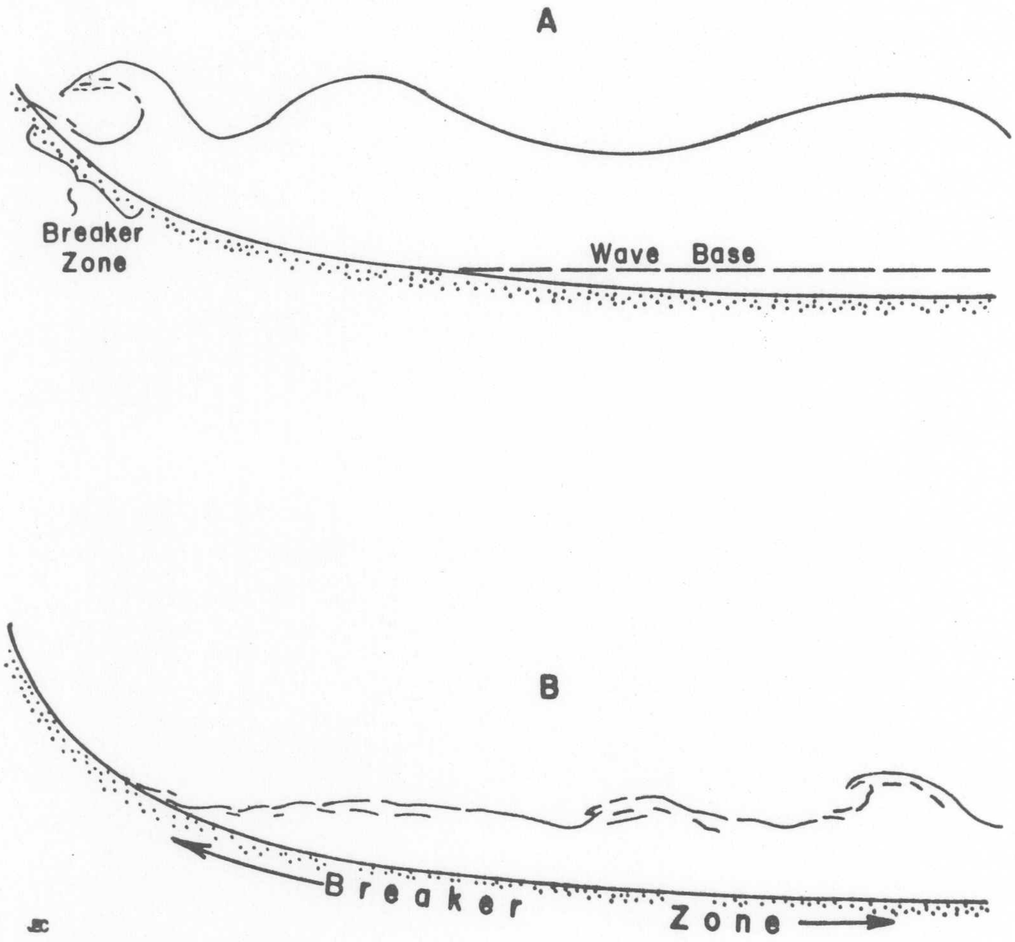


Figure 25: Breaker zones at high (A) and low (B) lake stage.

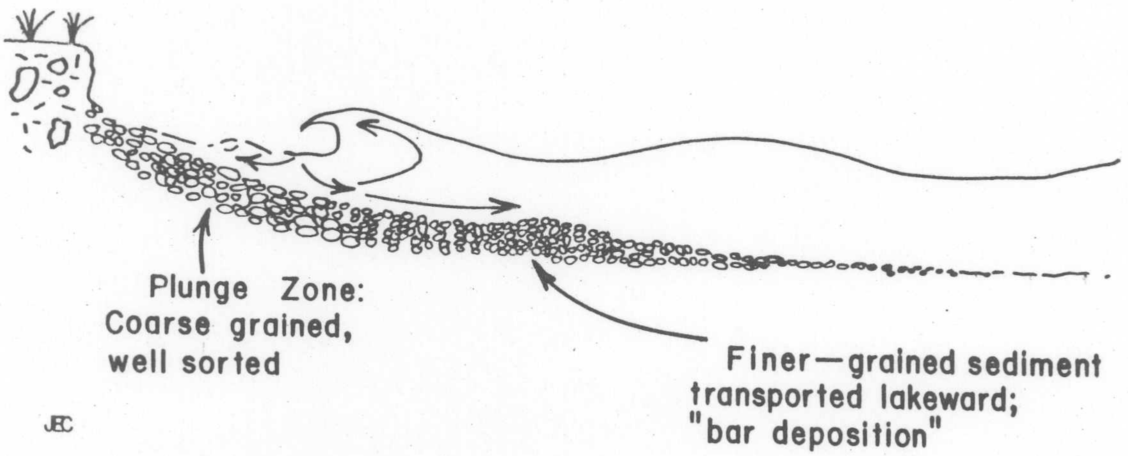


Figure 26: Sediment types associated with the beach area.

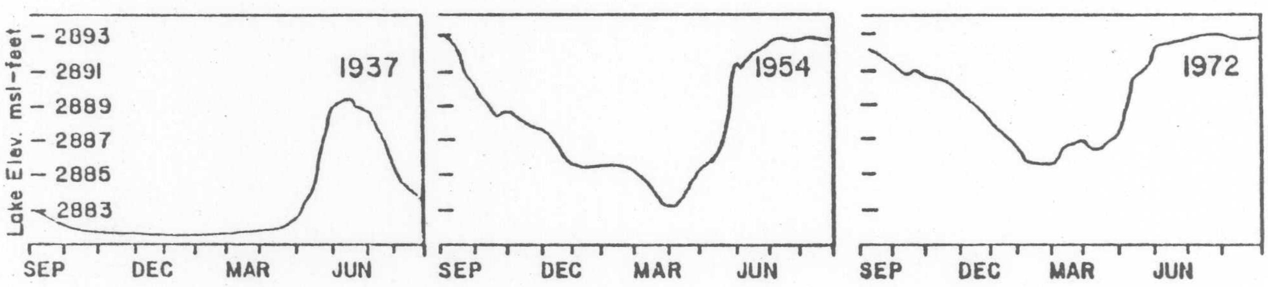


Figure 27: Flathead Lake hydrographs.

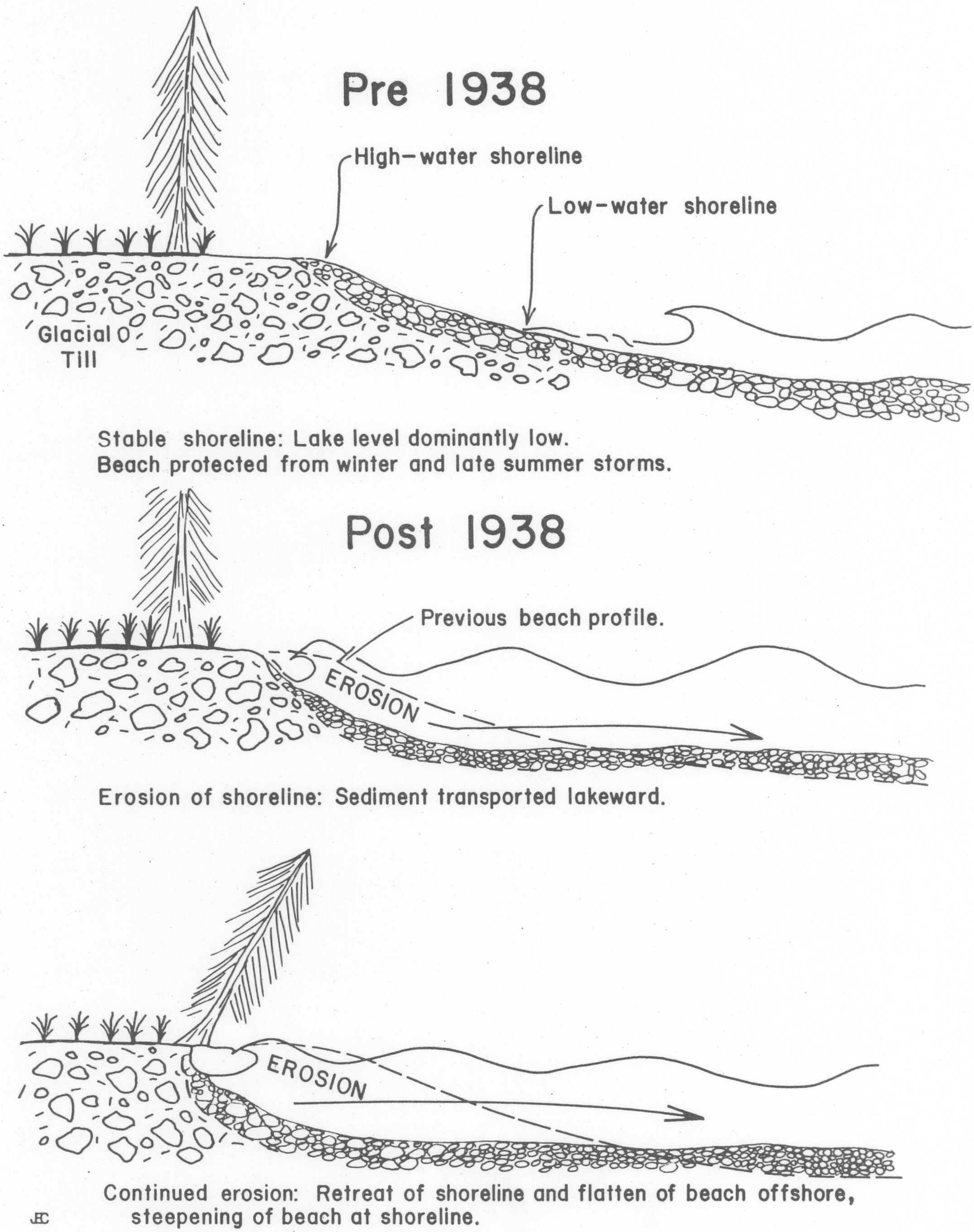


Figure 28: Schematic of the effects of lake stage position and operation pre and post 1938.

However, once the lake level was raised, a whole new wave dynamics would be established. At high elevations, waves would crash directly onto the shoreline in relatively deep water. Larger waves would be common at these high stands because the lake is kept at full stand for many months during the main storm seasons. The beach would respond to this increased energy in several ways. First, the shoreline would retreat. The sediment eroded from the shoreline would be transported onto the lower beach during storms and deposited over the previous beach (Figure 28). The upper beach profile would steepen as the shoreline retreated and remain steep until a new equilibrium could be established. Although the details of this adjustment would depend on many factors, undoubtedly the sediment on the beach would be considerably more mobile because it was acted upon by many more waves of higher energy.

The rate and magnitude of these changes would depend on the location of the beach and the material of which it was composed. Shores of resistant bedrock would show very little change over short periods of time (tens of years); whereas beaches developed on glacial till, or older alluvial sediment, would respond nearly instantaneously. The position and trend of the shoreline will also modify the change. Beaches that are oriented so that they receive the full brunt of storm waves will change more quickly than those protected in bays or other sites.

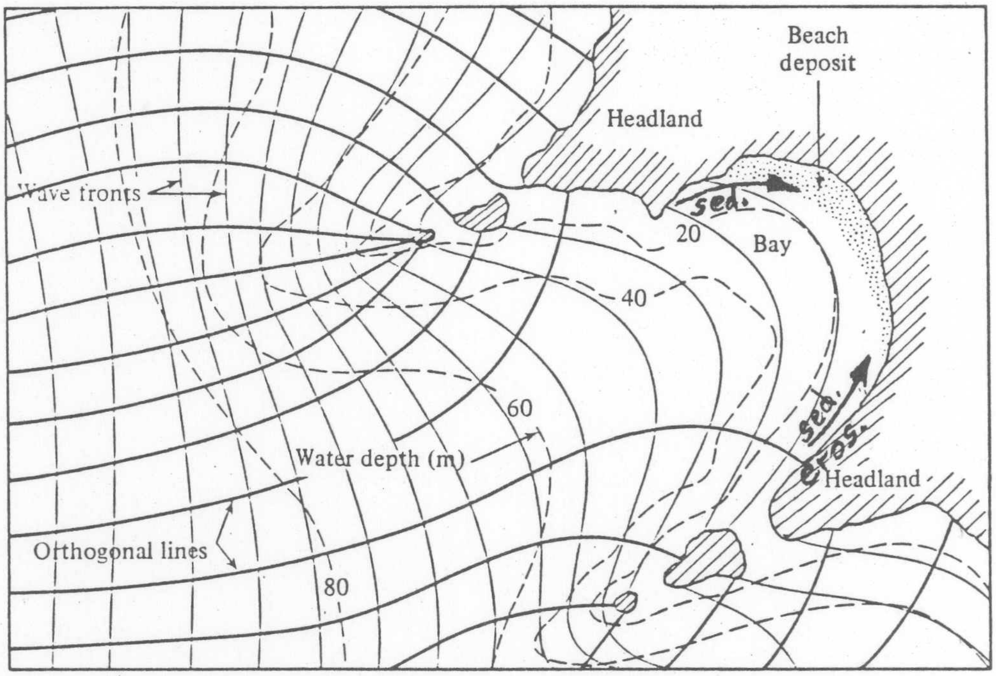
When waves are generated in one end of the lake, they travel as free waves until they encounter the bottom. They will then refract around headlands and disperse into bays (Figure 29). This concentrates wave energy on the headlands and tends to transport sediment into smaller bays. As well the refraction of waves along a linear shoreline causes longshore transport of sediment. If sediment transport is disrupted by piers or docks, sediment will accumulate on the upcurrent side and erode from the downcurrent side (Figure 30). Again, these processes will be accentuated by high lake levels when more wave energy can be expended on the upper beach and more sediment is added by erosion of the shore. Such erosion and redeposition has occurred at a dramatic level along the north shore of Flathead Lake resulting in the destruction of Flathead River delta and the accompanying habitat.

Between 1937 and 1981, more than 8 sq km of sediment was removed from the Flathead Lake delta plan (Figure 31) on the north shore. Sediment was eroded to a depth of 1.5 m exposing roots of trees and completely removing the other vegetation (Moore et al., 1982). What was once a prime habitat for migratory water fowl, is now a broad sand plain submerged most of the year beneath several feet of water. This destruction resulted from increased erosion when the lake elevation remained high during the storm seasons (Figure 32).

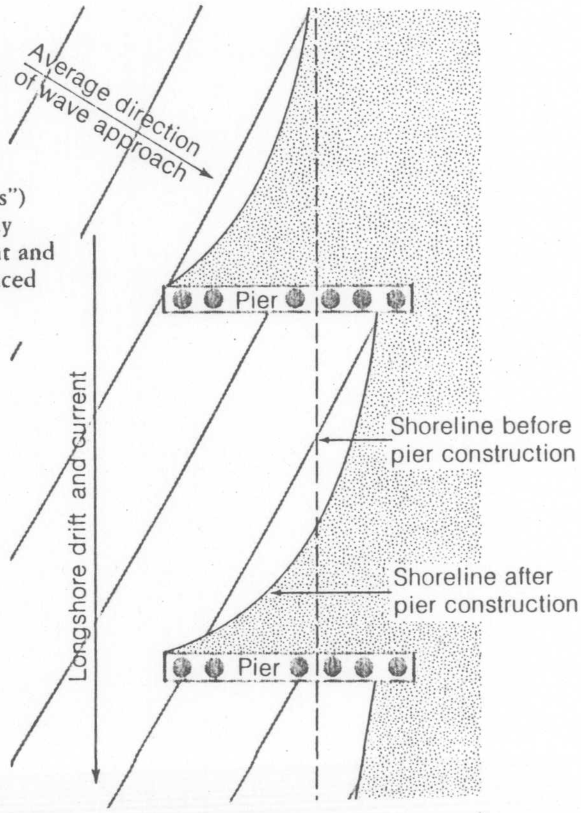
ALTERATIONS OF SHORELINES AS SEEN FROM AERIAL PHOTOGRAPHS

In this section the changes in shoreline morphology resulting from increased erosion and deposition from unnaturally high lake elevations are discussed. Although these changes are not nearly as dramatic as the destruction of the delta, they extend around the lake and likely affect nearly every part of the shoreline. However, because of the lack of detailed photographic coverage of the entire lake shore, only isolated areas that emphasize the processes of shoreline modification are discussed.

Figure 29: Wave refraction and sediment transport



As the waves "feel bottom" first in the shallow areas off the headlands, they are slowed. The segments of the waves that move through the deeper water leading into the bay are not slowed until they are well into the bay. As a result, the waves are *refracted* (bent) so energy is concentrated on the stacks and headlands. Erosion is active on the headlands, while deposition occurs in the bay where the energy level is low. Orthogonal lines spaced so that equal amounts of energy are between each line help to show the distribution of energy along the shore.



Construction of piers (frequently called "groins") along a shore to control erosion of a beach may produce unwanted changes if longshore current and drift are not considered. A typical change induced is erosion downcurrent of the pier.

Figure 30: Effects of pier and groin construction on sediment transport.

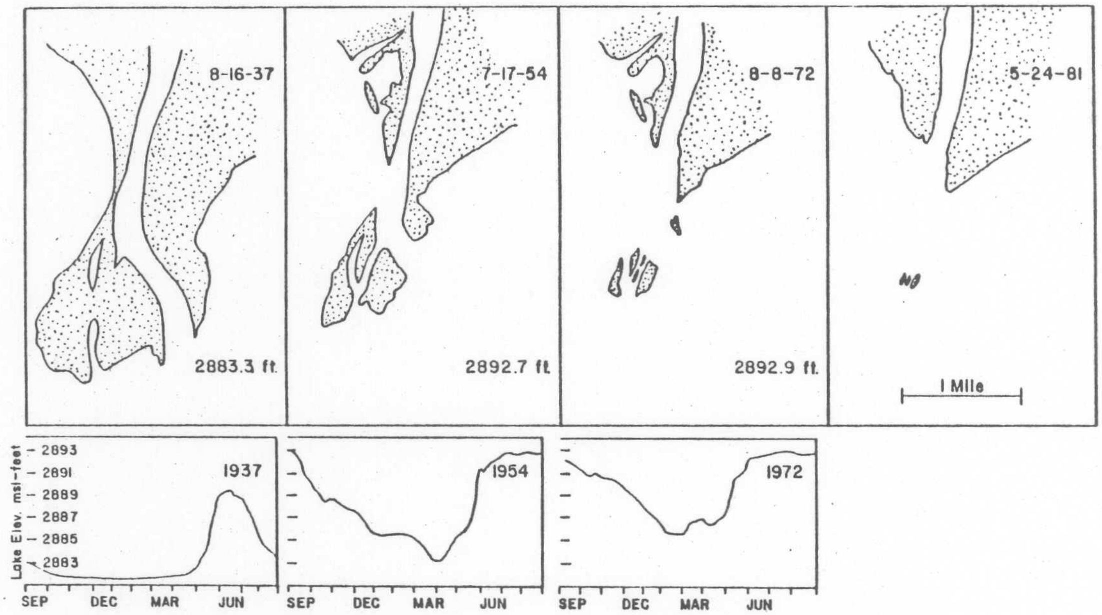


Figure 31: Changes in the Flathead River Delta, 1937 to 1981 (after Moore et al., 1982)

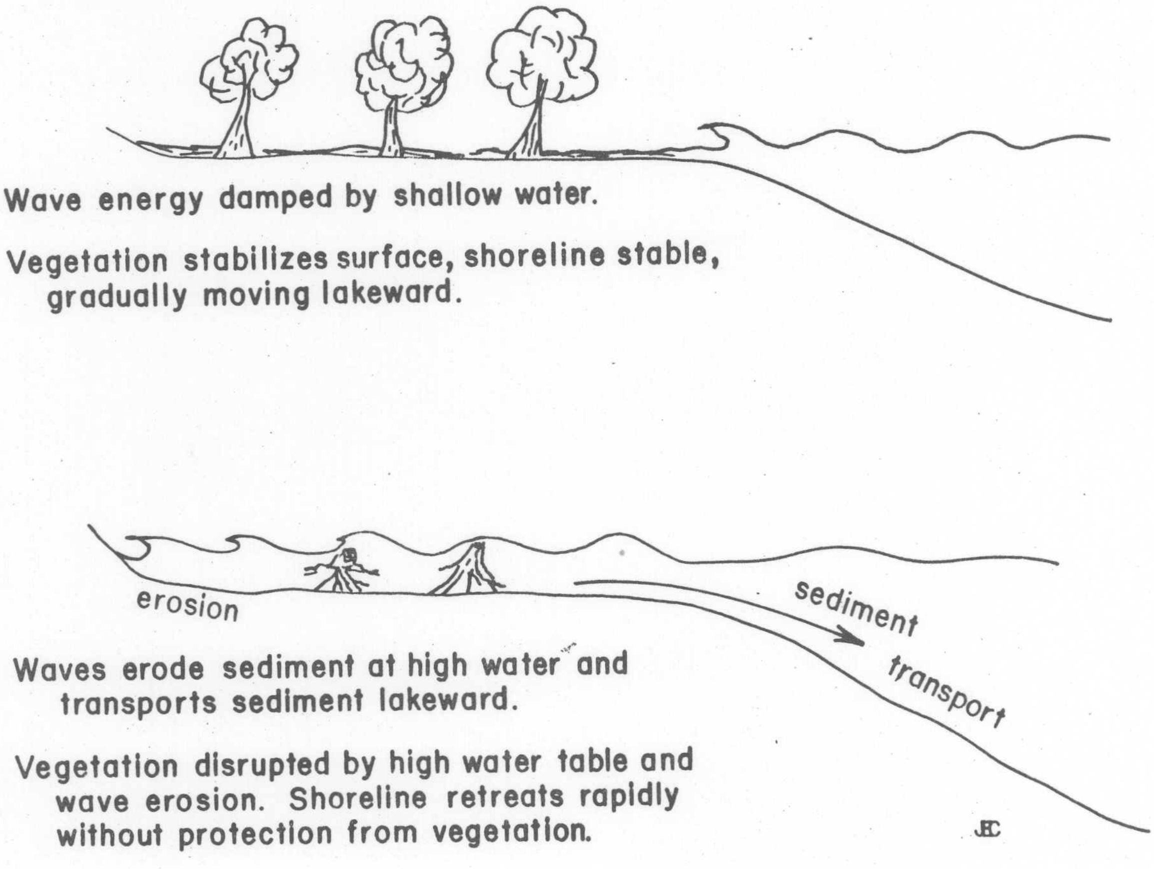


Figure 32: Processes effecting delta stability

Point Caroline

Point Caroline shows significant shoreline modification since construction of Kerr Dam. On July 30, 1935, the broad beach surrounding the point is exposed by a low lake elevation (LE) of 2885.5 ft, 6.5 ft below the maximum stand in early June. The extent of the beach deposits can be seen to extend below the surface of the lake outwards of shore. An August 16, 1937, photograph shows nearly identical fine scale features, including the small protrusion at the south end of Point Caroline and the broad beach protecting the low depression between the point and the peninsula (point A, Figures 33 and 34). A lake elevation of 2883.5 has exposed a bit more of the beach. The width of the beach south of Point Caroline is different than that to the north. The southward-facing, southern beach ranges from 150 to 200 ft wide; the beach extending from Point Caroline to the bay to the north, the eastward-facing beach, averages 110 ft wide. Over this two-year period, there has been no modification of the shoreline of any significance. Small features can be seen on both photographs that have remained unmodified by shoreline processes.

By September 2, 1954, the barrier between the small field and the lake has been removed (either by wave erosion or development) and the lake now extends into the depression forming a shallow bay. Although the resolution in the 1935 and 1937 photographs is poor, it appears that the lake did not extend directly into this depression previous to 1954. In less than 20 years, after the lake level rose, the bay was deepened by either wave erosion or dredging and the broad beach separating it from the beach completely destroyed and replaced by an inlet 190 ft wide. Even at the high lake elevation of 2893 ft in 1954, the submerged beach deposits can be seen extending away from the shoreline. They have become somewhat discontinuous and sediment can be seen accumulating in linear offshore bars (point C, Figure 35), and newly constructed docks have started to disrupt sediment transport along the beach south of Point Caroline. Sediment transported southwestward has accumulated on the eastern sides of the docks and caused erosion of material from the westward side. The head of the bay to the north of Point Caroline has retreated nearly 230 ft from its 1937 position, and sediment that formed a distinctive bar in the head of the bay has been completely removed and smoothed into a gentle slope (point B, Figures 33, 34 and 35).

At the same lake elevation (2893 ft) on August 8, 1972, the shoreline can be seen to have narrowed and become more irregular (Figure 36). The pass into the small bay has closed to 190 ft by the building of small spit of material from the west bank. The bay appears quite deep suggesting that a large amount of sediment has been removed by either wave erosion or dredging. The pre-1938 beaches are completely gone and there is no indication of extensive beach deposits extending shoreward, even though the water appears quite clear. The beach has become a narrow strip of sediment less than a few tens of feet wide and appears much steeper. The head of the northern bay has retreated another 40 ft (point B, Figure 36) and straightened as a result of continued wave erosion.

By May 5, 1981, (LE = 2891 ft) the shoreline has been heavily developed and apparently stabilized (Figure 37). Relatively little change has taken place since the last (1972) photograph other than the incorporation of the shoreline into the overall recreational development. The lake water is opaque so no observations can be made on the extent of the submerged beach deposits.

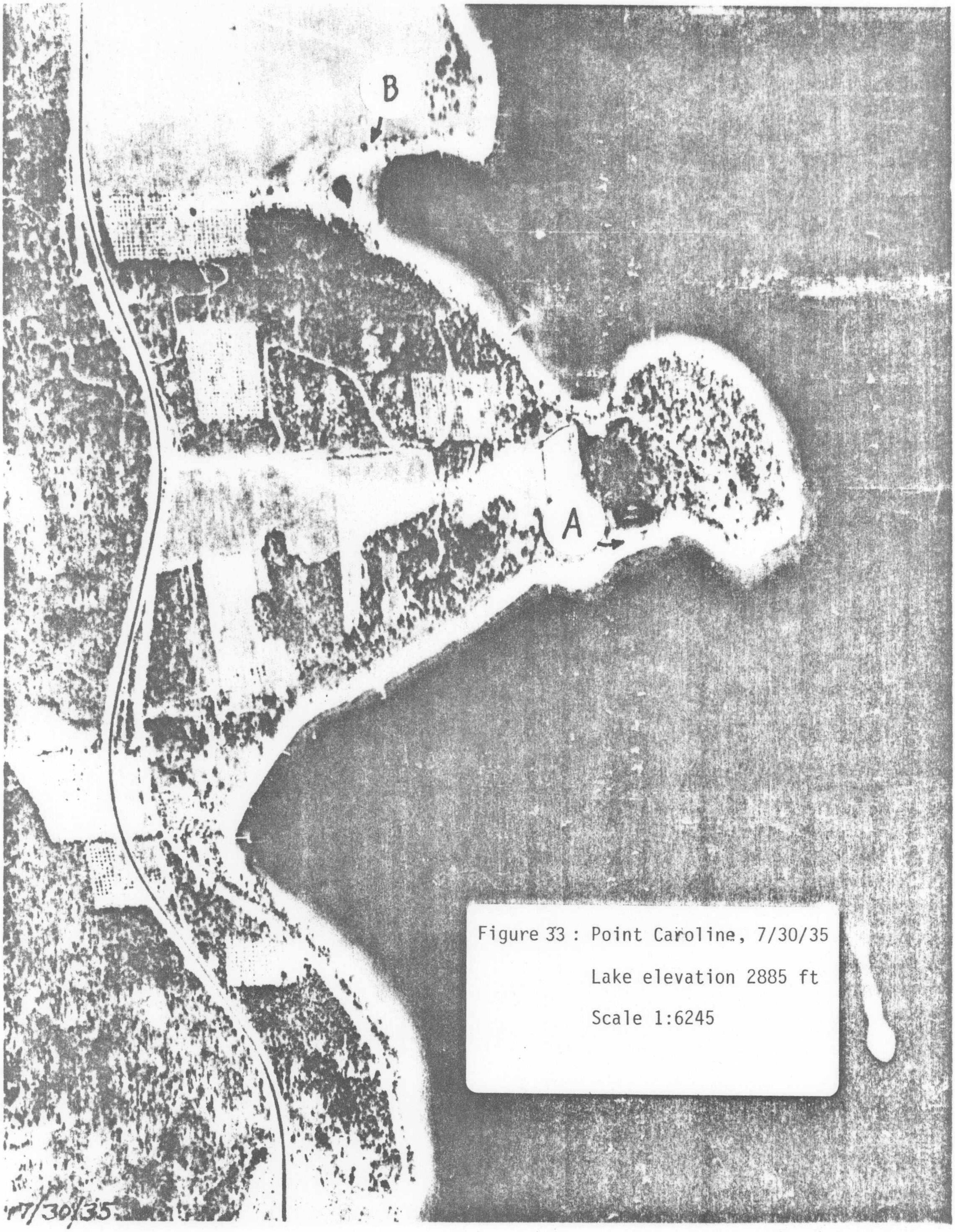


Figure 33 : Point Caroline, 7/30/35

Lake elevation 2885 ft

Scale 1:6245

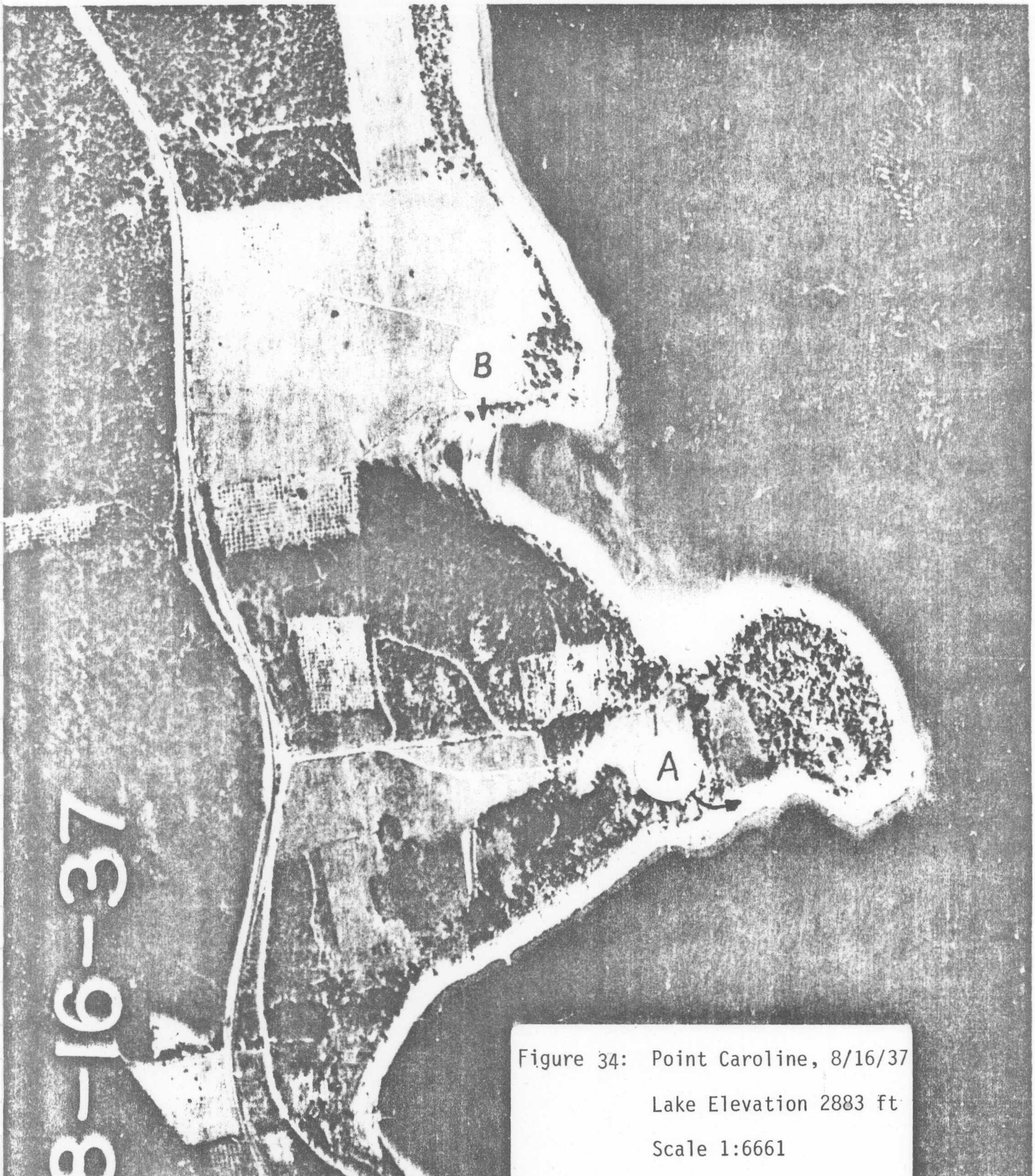


Figure 34: Point Caroline, 8/16/37

Lake Elevation 2883 ft

Scale 1:6661

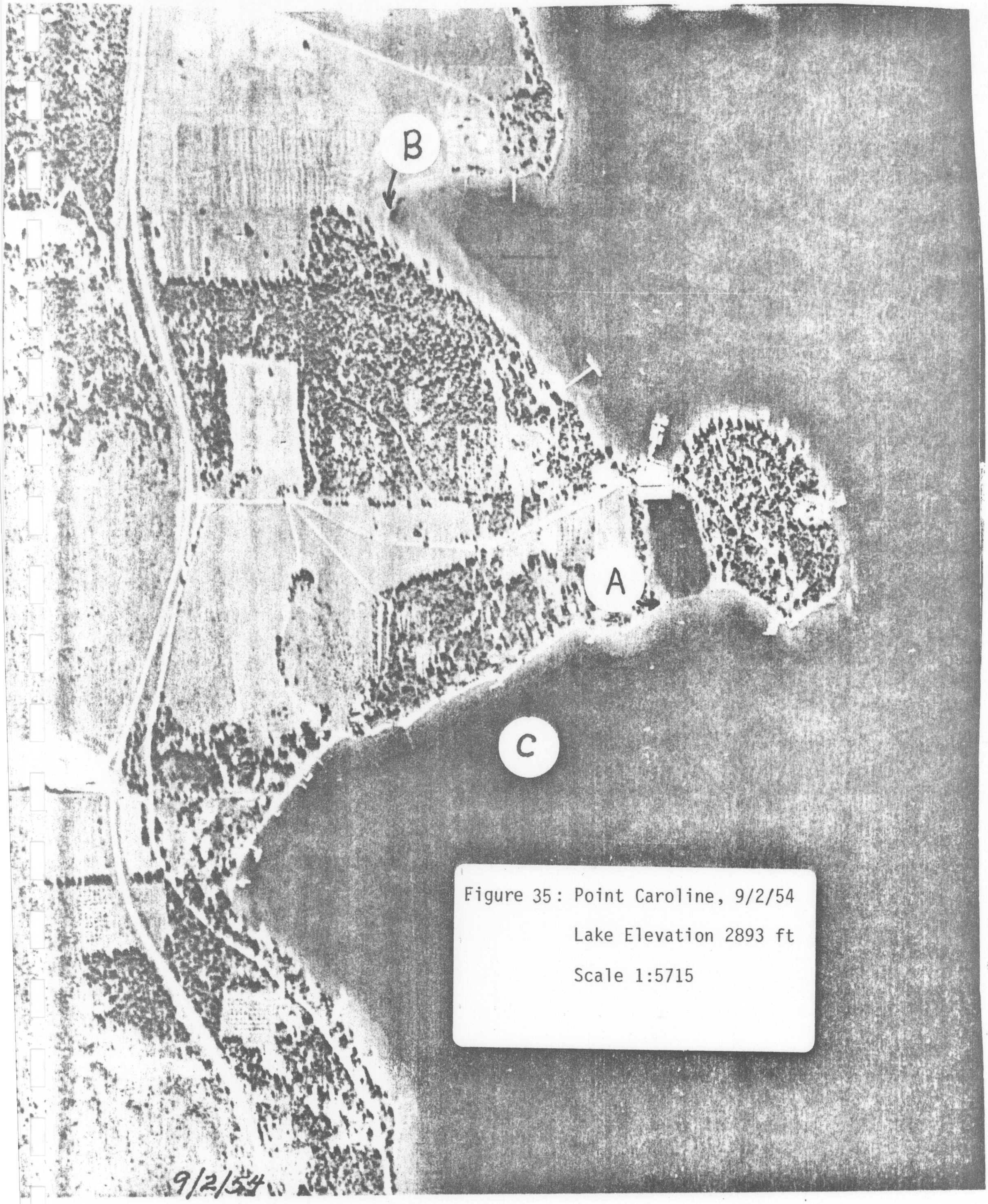


Figure 35: Point Caroline, 9/2/54

Lake Elevation 2893 ft

Scale 1:5715

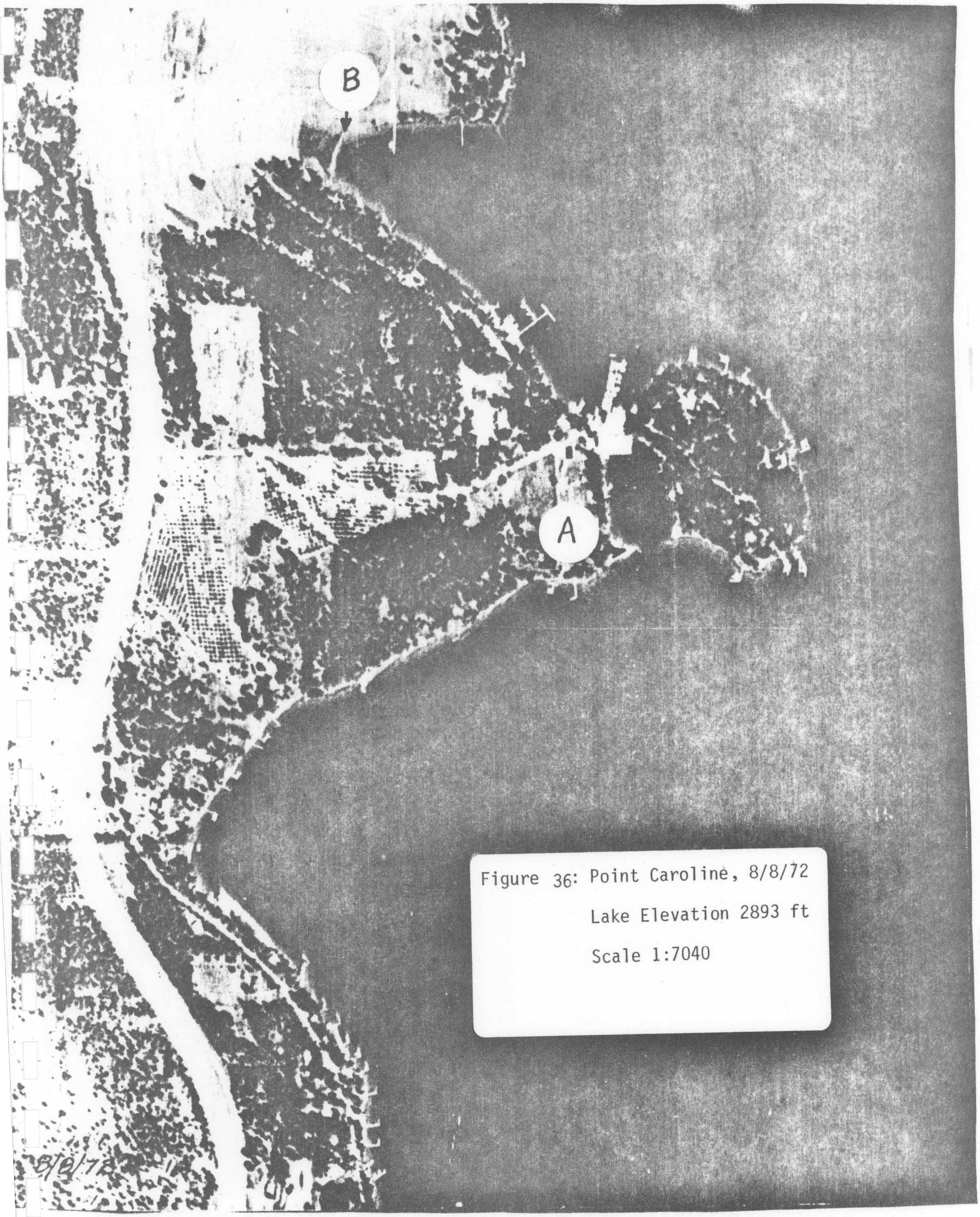


Figure 36: Point Caroline, 8/8/72

Lake Elevation 2893 ft

Scale 1:7040

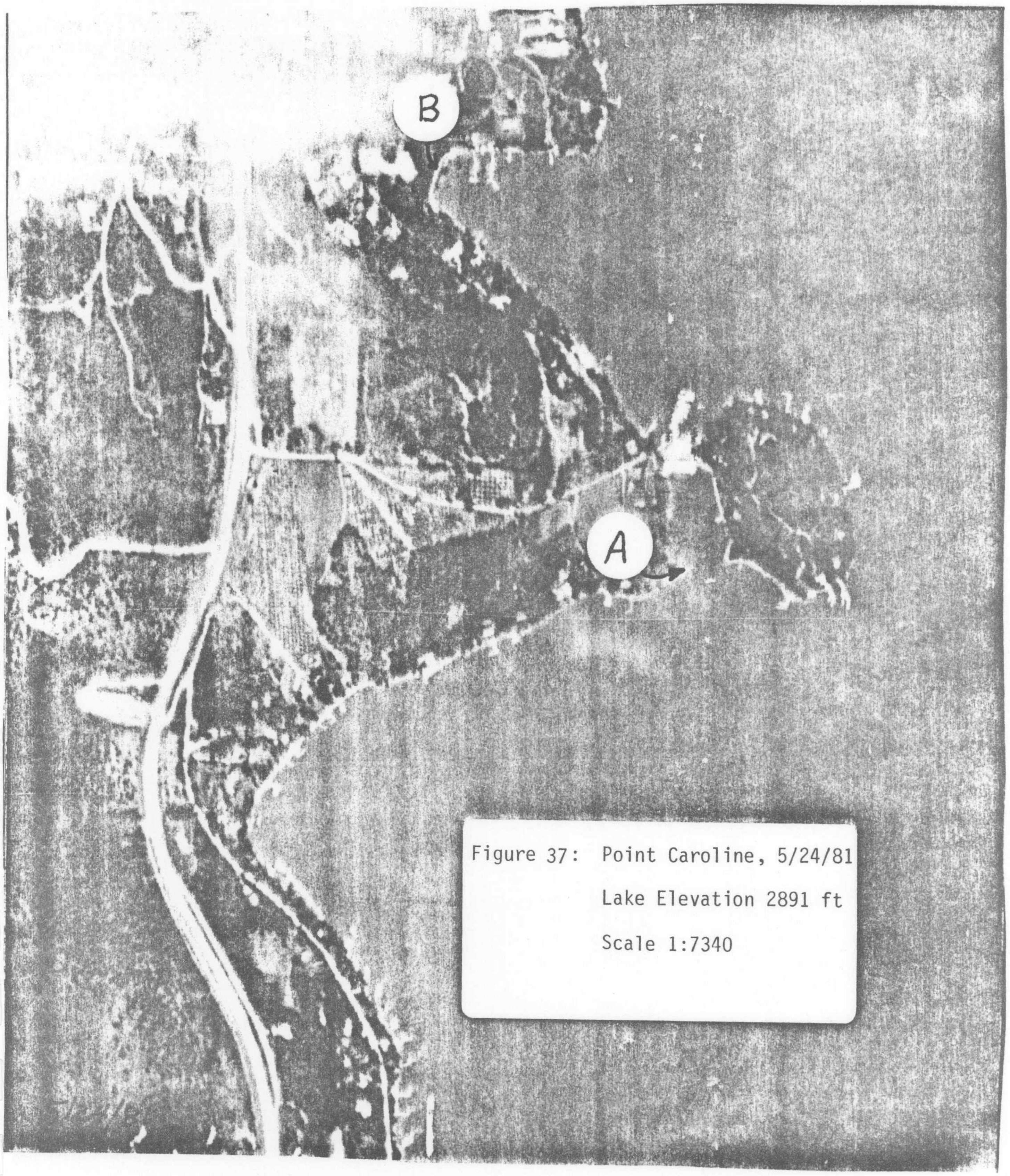


Figure 37: Point Caroline, 5/24/81

Lake Elevation 2891 ft

Scale 1:7340

Aerial photographs of the Point Caroline shoreline show that since the construction of Kerr Dam, there has been significant beach erosion. What was once a broad, relatively gently-sloping beach has become a narrow strip of sediment. Bays and parts of "dry land" have been completely eroded and sediment presumably transported into the lake. It appears that most of the modification occurred between 1938 and 1954. Between 1954 and 1972 the changes were much less dramatic and apparently slowed significantly thereafter. It seems quuite likely that this erosion and modification resulted from the artificially high lake elevations maintained since the construction of Kerr Dam, allowing storm waves access to upper beach deposits. Erosion and beach modification appears to have slowed significantly as the shoreline approaches a new equilibrium with the higher lake levels.

Woods Bay

The photographic coverage of Woods Bay is restricted to 1954 and younger, and therefore the baseline configuration is unavailable. This is unfortunate because the Point Caroline shoreline showed the most modification between the 1937 and 1954 photographs. Even though the first major modifications may have been missed, significant change has been recorded on the later photographs.

On September 1, 1954, (LE = 2893 ft) gentle slopes can be seen extending from some of the headlands into deeper water. Beach deposits are widest in the coves (upwards of 200 ft) and narrow on the headlands (as low as 80 ft). The few docks present show a significant accumulation of sediment, indicating a northward drift (point A, Figure 38). A small spit has already built northward 80 ft from the western point of Woods Bay Point at the high water stand elevation (point B, Figure 38) beginning to enclose a stretch of beach.

Sequential photographs show that these processes continued through 1981 (Figures 39, 40 and 41). In 1966 the beaches appear somewhat narrower on the points and somewhat broader in the bays. Sediment transport to the north has built the western spit to a length of 140 ft, and the shore directly northeast of its tail appears to be eroding somewhat. By 1972, the spit had grown to 205 ft, but the other shoreline features appear to have stabilized. Between 1972 and 1981 the western spit eroded, shortening to a length of 175 ft.

It appears that the main shoreline dynamics at Woods Bay were developed well before 1954, the date of the first aerial photographs. Since then, waves continued to transport sediment northward and deposit sediment in the bays. This configuration is the expected one for waves originating in the south and refracting into the bay. By 1954, the beaches already appear steep, and it is therefore impossible to determine the changes immediately following the raise in lake elevation. It is very apparent, however, that sediment has been extremely mobile as indicated by prisms of sediment accumulating along docks and off the western point. The buildup of sediment at the high water mark ties this mobility to raised lake levels. It is likely that this mobility increased significantly and the shoreline was modified rapidly immediately after the increased lake elevation in 1938.

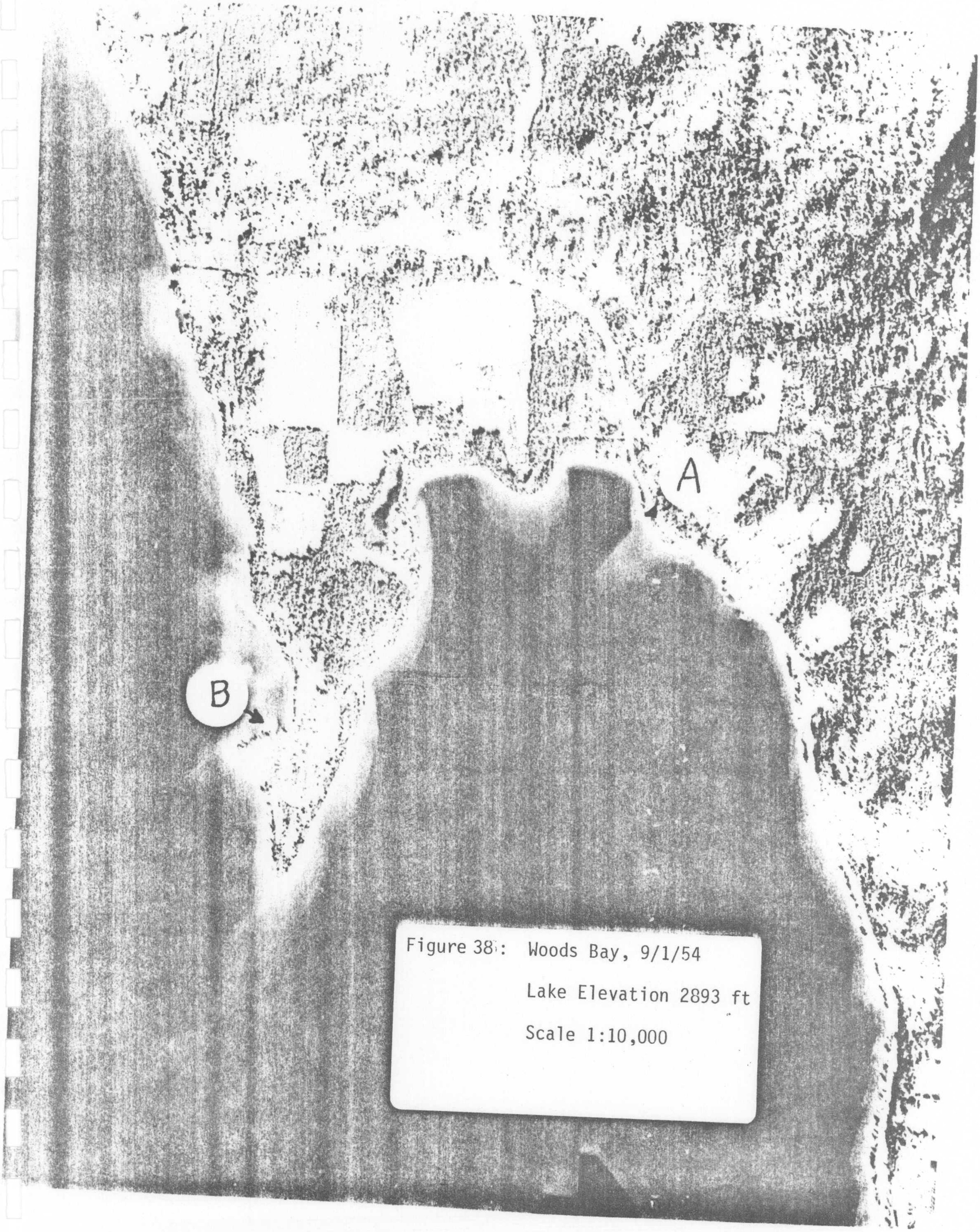


Figure 38: Woods Bay, 9/1/54

Lake Elevation 2893 ft

Scale 1:10,000

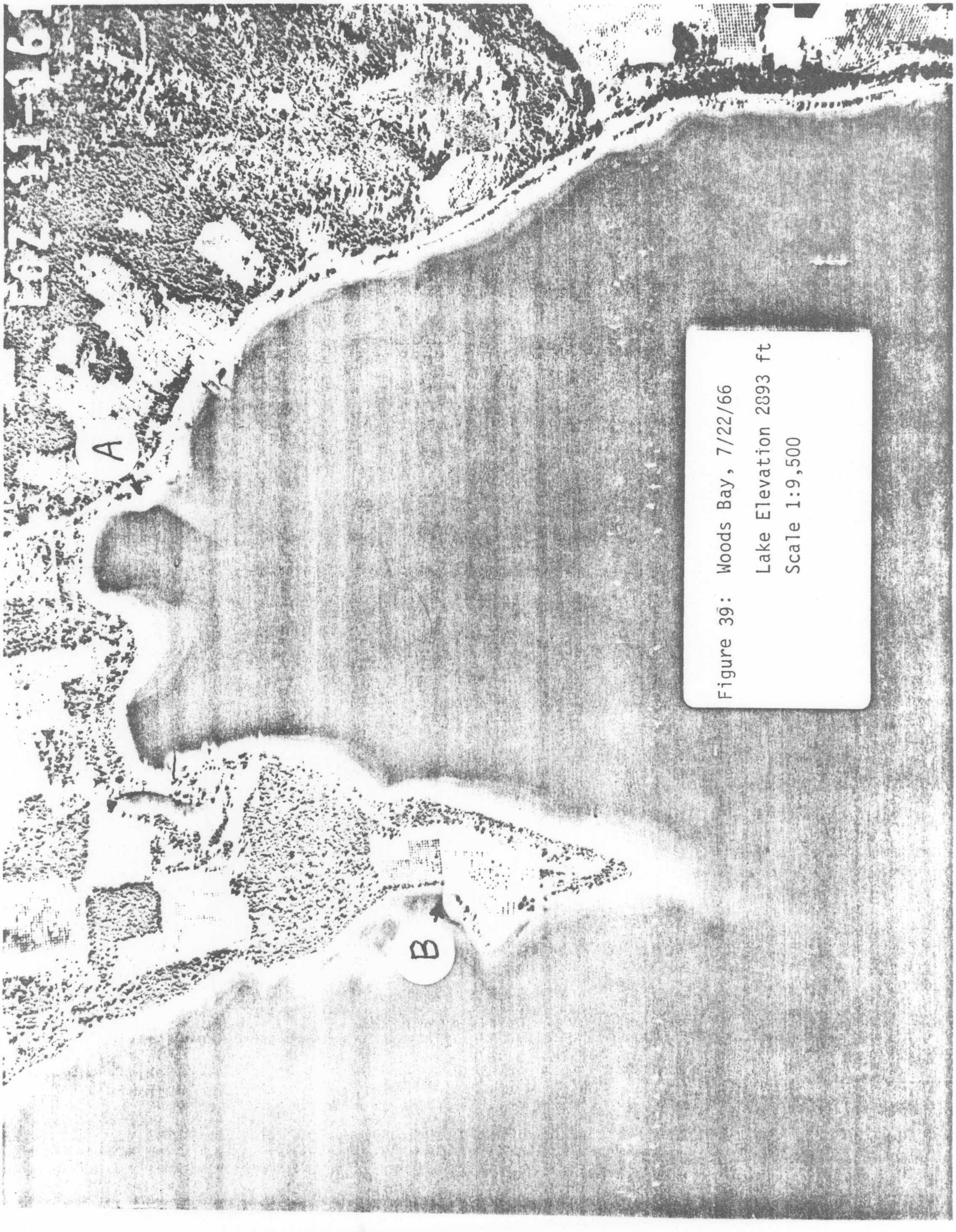


Figure 39: Woods Bay, 7/22/66
Lake Elevation 2893 ft
Scale 1:9,500

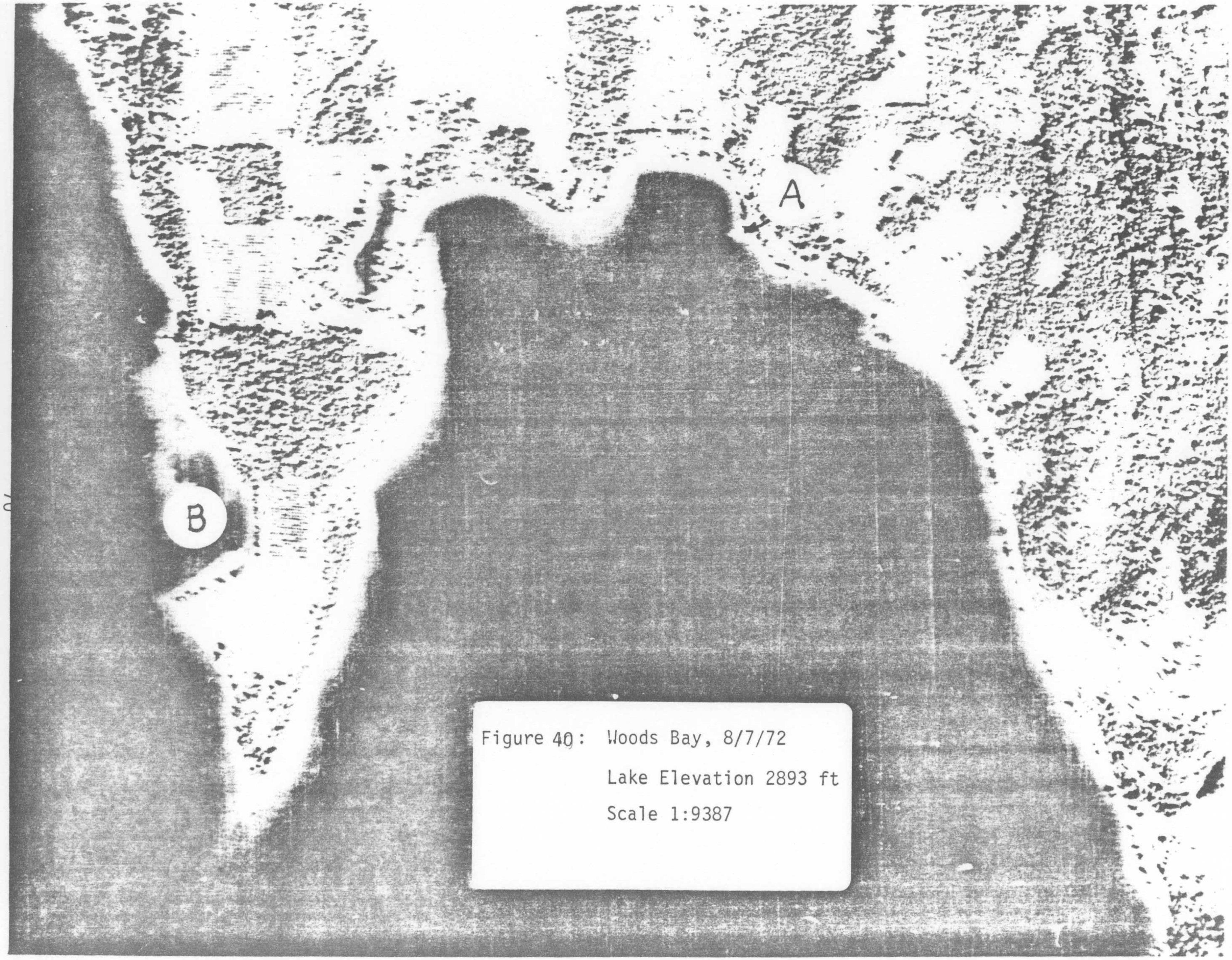


Figure 40: Woods Bay, 8/7/72

Lake Elevation 2893 ft

Scale 1:9387

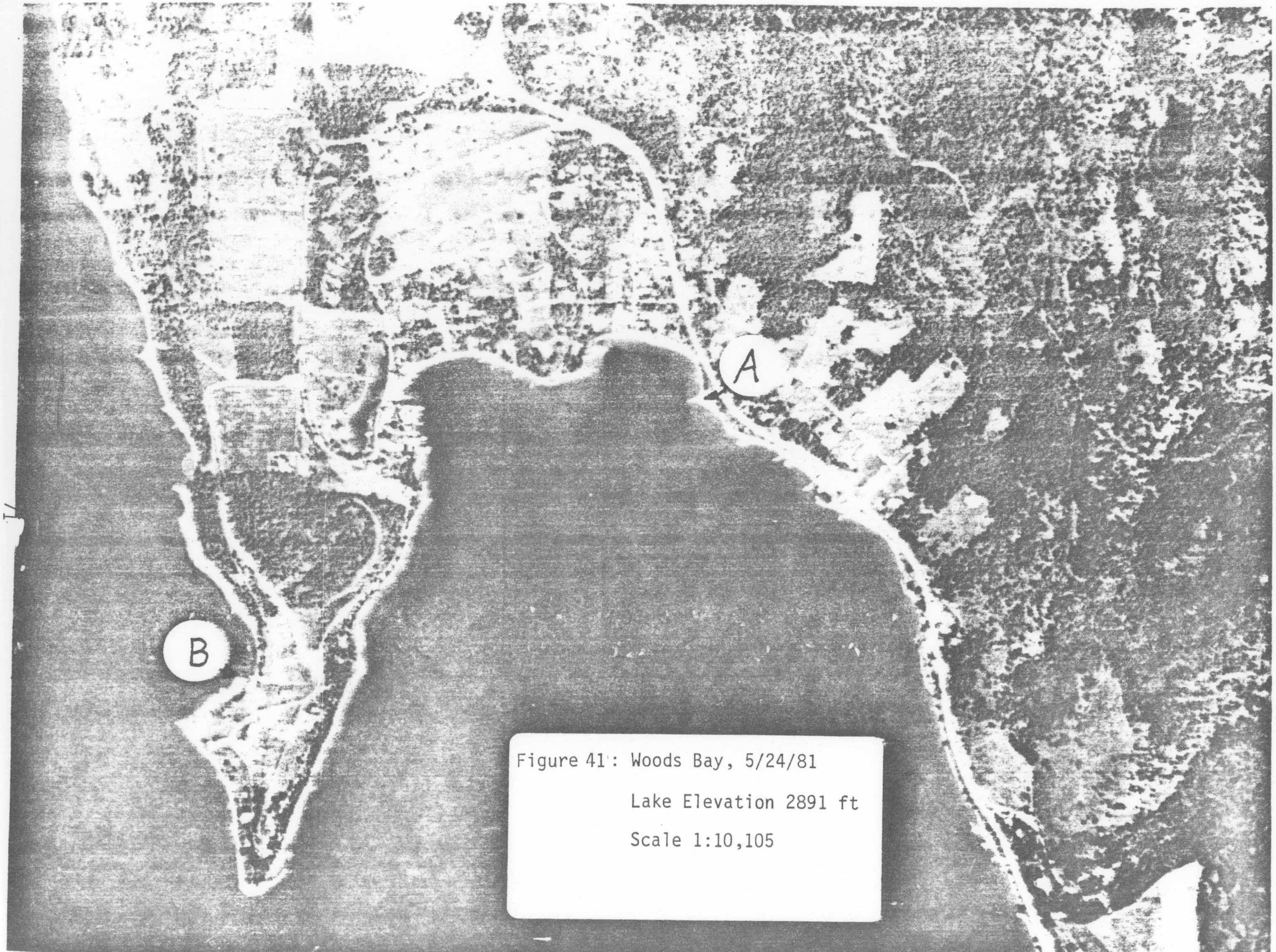


Figure 41: Woods Bay, 5/24/81

Lake Elevation 2891 ft

Scale 1:10,105

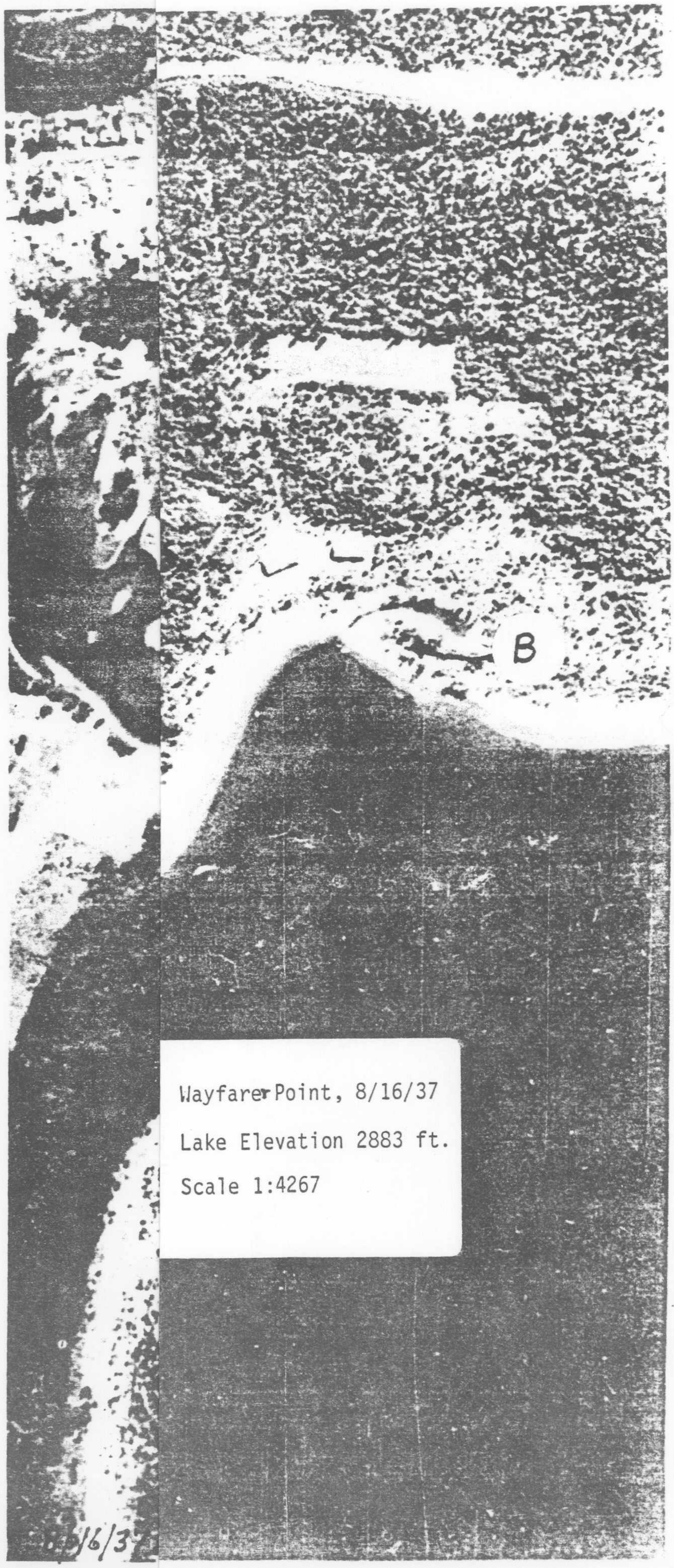
Swan River Inlet

The shoreline near the inlet of the Swan River has shown the most dramatic modification since construction of Kerr Dam. On August 16, 1937, the inlet contained a complex and extensive accumulation of sediment (Figure 42). A striking spit (point A, Figure 42) extended north into the river from Wayfarer Point, undoubtedly formed by northward-flowing longshore currents. A smooth, continuous beach approximately 125 ft wide extended south of Wayfarer Point thickening into the bay to the south. The bay contains a wide ridge with a small depression behind it (point B, Figure 42). Beach deposits can be seen extending below the lake surface (LE = 2883.5 ft) forming a distinct broad beach deposit.

By September 2, 1954, this shoreline had undergone extreme modification (Figure 43). Even at the higher lake elevation (LE = 2893 ft) visibility is good down into relatively deep water so that the Wayfarer spit can be seen extending northward, completely submerged beneath the higher lake level. The vegetation on the spit has entirely disappeared and the width has halved. To the south the width of beach deposits have decreased to approximately 100 ft and the beach remoed entirely from around Wayfarer Point. The bay to the south has been eroded and the ridge separated from the shore (point B, Figure 43) reducing it from a width in 1937 of 125 ft to 55 ft in 1954. The shoreline of the bay has retreated to the east by approximately 70 ft. The north shore of Flathead Lake has been submerged and the vegetated shoreline has retreated to the north.

These changes continue on subsequent photographs (Figures 44 and 45). By August 7, 1972, the main components have stabilized. The beach south of Wayfarer has decreased to a width of 85 ft. The Wayfarer spit (point A, Figure 44) is a vague shadow beneath the lake (LE = 2893 ft). The spit in the southern bay (point B, Figure 44) has narrowed somewhat and its southern end remains attached to the shore by a thin strip of land. By May 24, 1981, (LE = 2891 ft) the small southern bay has been developed and highly modified by construction (point B, Figure 45). Northward sediment transport has built up on the south side of numerous docks and the Wayfarer spit is a vague remnant (point A, Figure 45). A new spit has begun building from a more northeasterly position on the point at the higher lake level (point A1, Figure 45). The north shore has also been completely developed and no evidence exists of the once (in 1937) extensive bar systems within the inlet of the Swan River.

The Swan River inlet and Wayfarer Point show significant modification by shoreline processes. The increased lake levels resulted in a shifting of the wave erosion processes farther up the beach. This nearly isolated the southern spit from the shore, decreased the width of the beach south of Wayfarer and submerged and destroyed the Wayfarer spit. As well the high lake levels inundated large areas of the north shore west of the Swan River, causing erosion and allowing development. The wave erosion continues presently building a new spit off Wayfarer Point at a higher elevation, leaving the old one flattened and submerged offshore. Such modifications could have formed only from an increase in lake elevation during the time of spit building. It is quite likely that such processes are ongoing around the lake shore, even in places where the scale of change does not show up on aerial photographs.



Wayfarer Point, 8/16/37

Lake Elevation 2883 ft.

Scale 1:4267

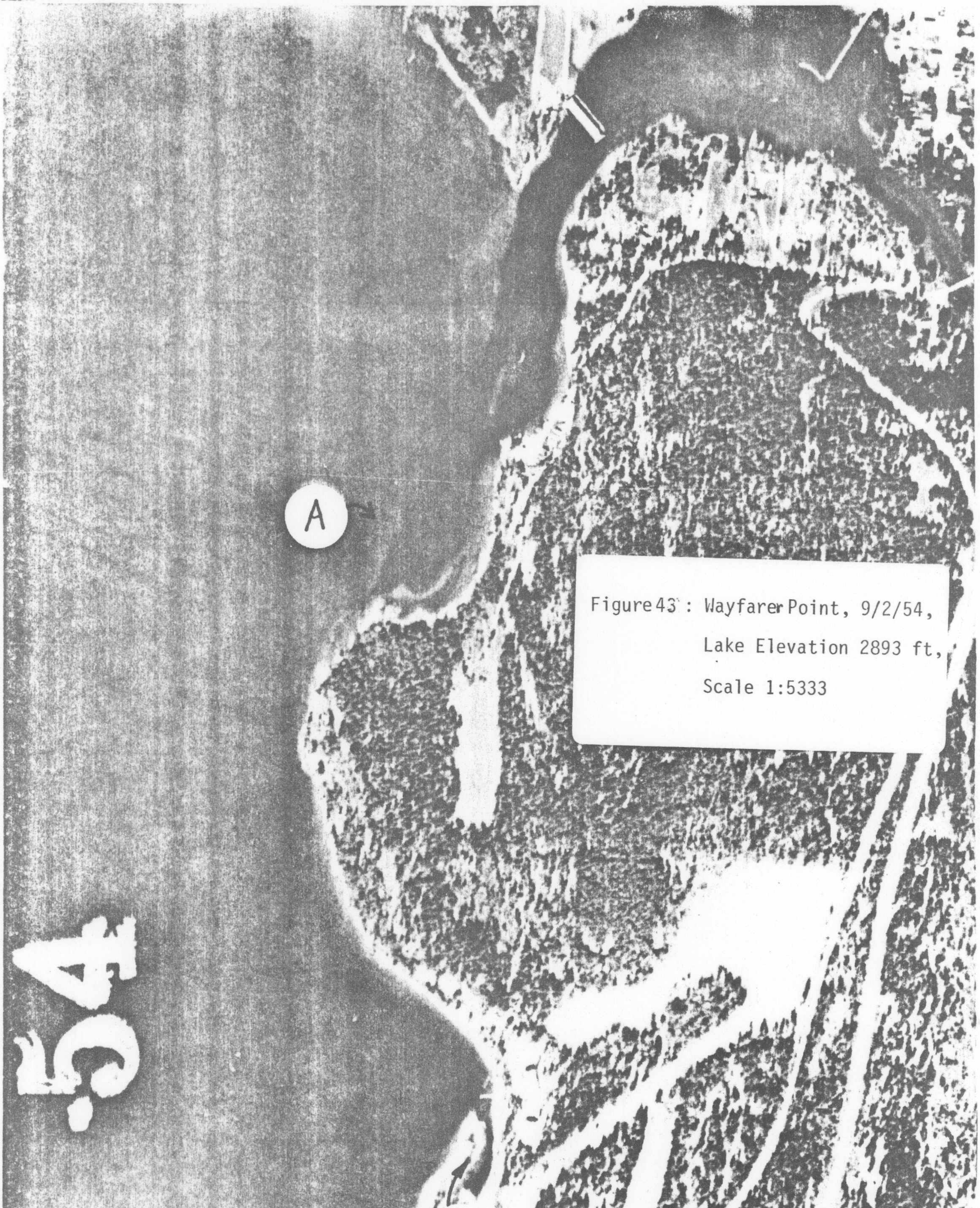


Figure 43 : Wayfarer Point, 9/2/54, Lake Elevation 2893 ft, Scale 1:5333

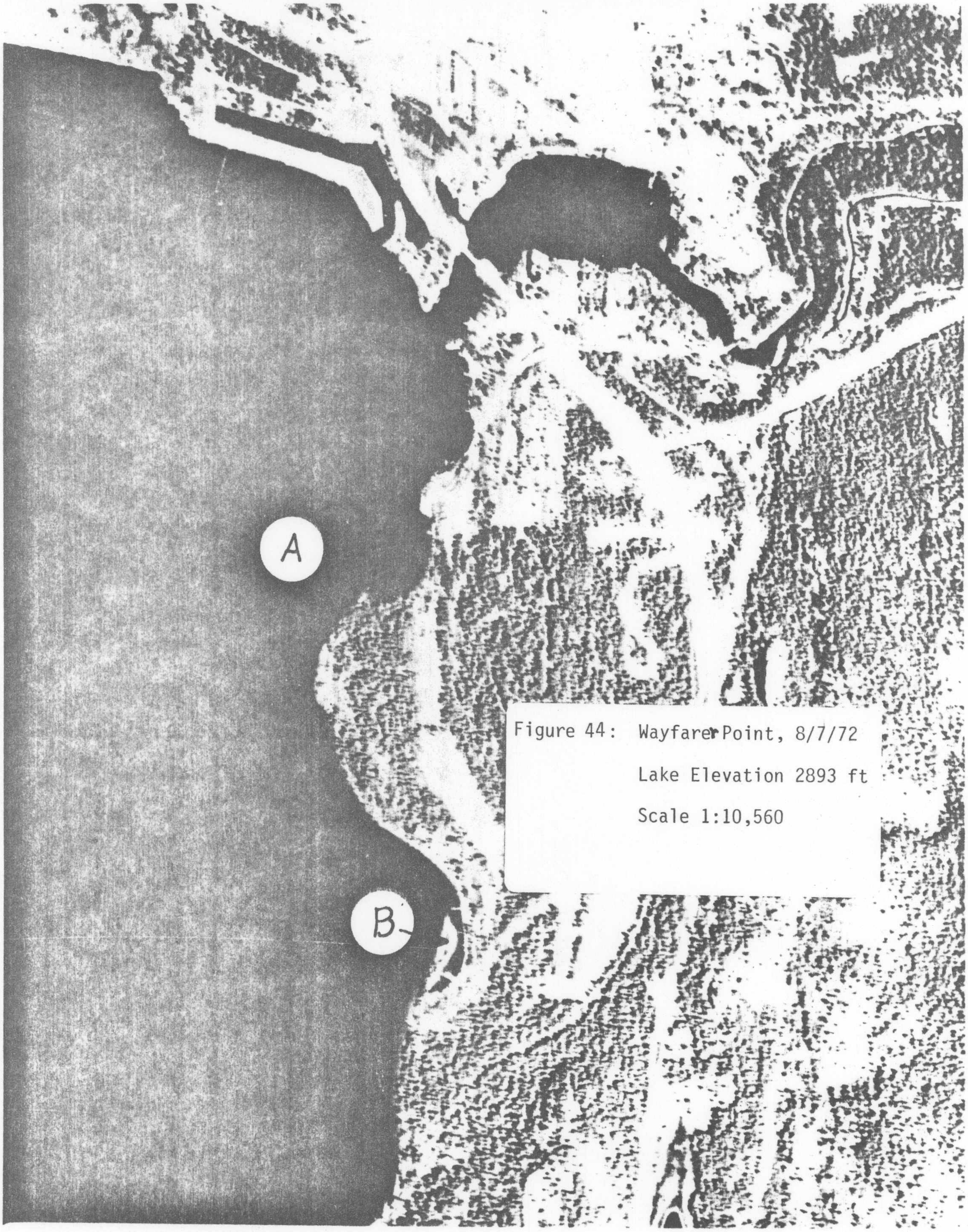


Figure 44: Wayfarer Point, 8/7/72
Lake Elevation 2893 ft
Scale 1:10,560

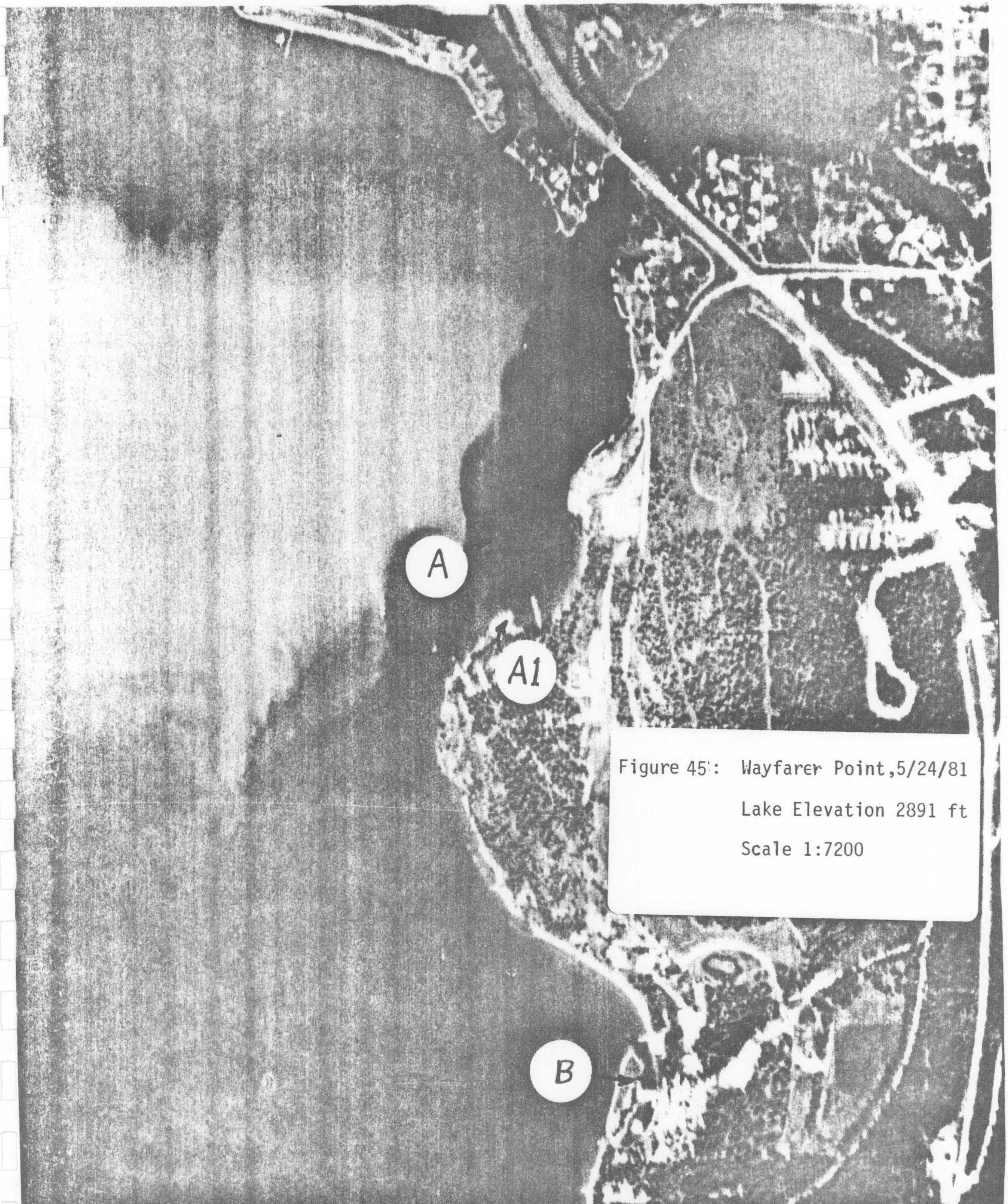


Figure 45: Wayfarer Point, 5/24/81
Lake Elevation 2891 ft
Scale 1:7200

Skidoo Bay

Unfortunately, the aerial photographic coverage of Skidoo Bay is quite poor. Only the 1934 and 1981 photographs cover the area with reasonable resolution, and even these show very little detail (Figures 46 and 47). In 1934 the shoreline is completely undeveloped and a broad beach is exposed at a lake elevation of 2886 ft on July 11, 1934. Continuous offshore bars parallel the shoreline and extend lakeward many hundreds of feet (point B, Figures 46 and 47).

The gross morphology of the shoreline in 1981 looks quite similar to that of 1934. At a higher lake elevation of 2891 ft, it is difficult to compare features. There is clearly an increase in development and sediment has accumulated behind docks along the east and west shores of the bay. No obvious beach deposits extend away from the shoreline, but the difference in elevation again makes identification of these features tenuous. In general, the shoreline appears somewhat straighter and sediment appears to have been removed from the western side of the bedrock peninsula, projecting into the lake near the center of the bay (point A, Figures 46 and 47). As in 1934, bars of sediment parallel the shoreline, indicating sediment transport and deposition by waves from the north. The lack of distinct shoreline features, and poor resolution of the photographs, restricts more detailed interpretation. Measurements of the position of the shoreline compared to a road on Finley Point indicates changes in the shoreline on the order of 2 to 5%. This change is within the repeatability of the measurement so no major changes in shoreline position can be seen from the aerial photographs between 1934 and 1981. However, the shoreline could have been modified by many feet and not be discernible by these methods. It is quite apparent that sediment has been transported along the shoreline. The active and distinctive bars and sediment buildup along docks suggest strong wave activity. Undoubtedly, with an increased lake level, these processes would be transferred to higher elevations on the beach, producing some erosion and steepening of the beach (see Figure 28). This is an extremely likely place for major modification of beach profile and grain size, characteristics that are not discernible on aerial photographs. Some such changes can be observed seasonably in recent years.

Grain-size analyses, by Department of Fish, Wildlife and Parks personnel in 1983 and 1984, show a very dynamic system on the beaches of Skidoo Bay. Although the data shows a variety of grain sizes on the beach, the few samples taken sequentially in one location indicate rapid and significant change in wave energy and substrate size (Figure 48). At low water in 1983 (April), the sediment is composed dominantly of sediment greater than 50.8 mm. The remainder of the sediment was in the pebble and sand fractions. As the water rose, the relative percent of pebbles and sand decreased as the coarse fractions increased. In late May, this trend reversed and pebble-to-sand sizes increased somewhat as the coarsest fractions increased. By full pool the substrate has changed significantly, the greater than 50.8 mm fraction doubling. By the following winter when the lake level began to drop, the sediment had again changed. It then contained nearly 70% material between 50.8 and 16 mm in size. This suggests that these grain sizes were transported into the deeper water during the summer and fall. Through the remaining months of winter of 1984, the substrate grain size fluctuated widely. Over short intervals of time (two weeks), percent sediment in the 16 to 0.063 mm size ranged from over 50% (early January) to less than 25% (late January).

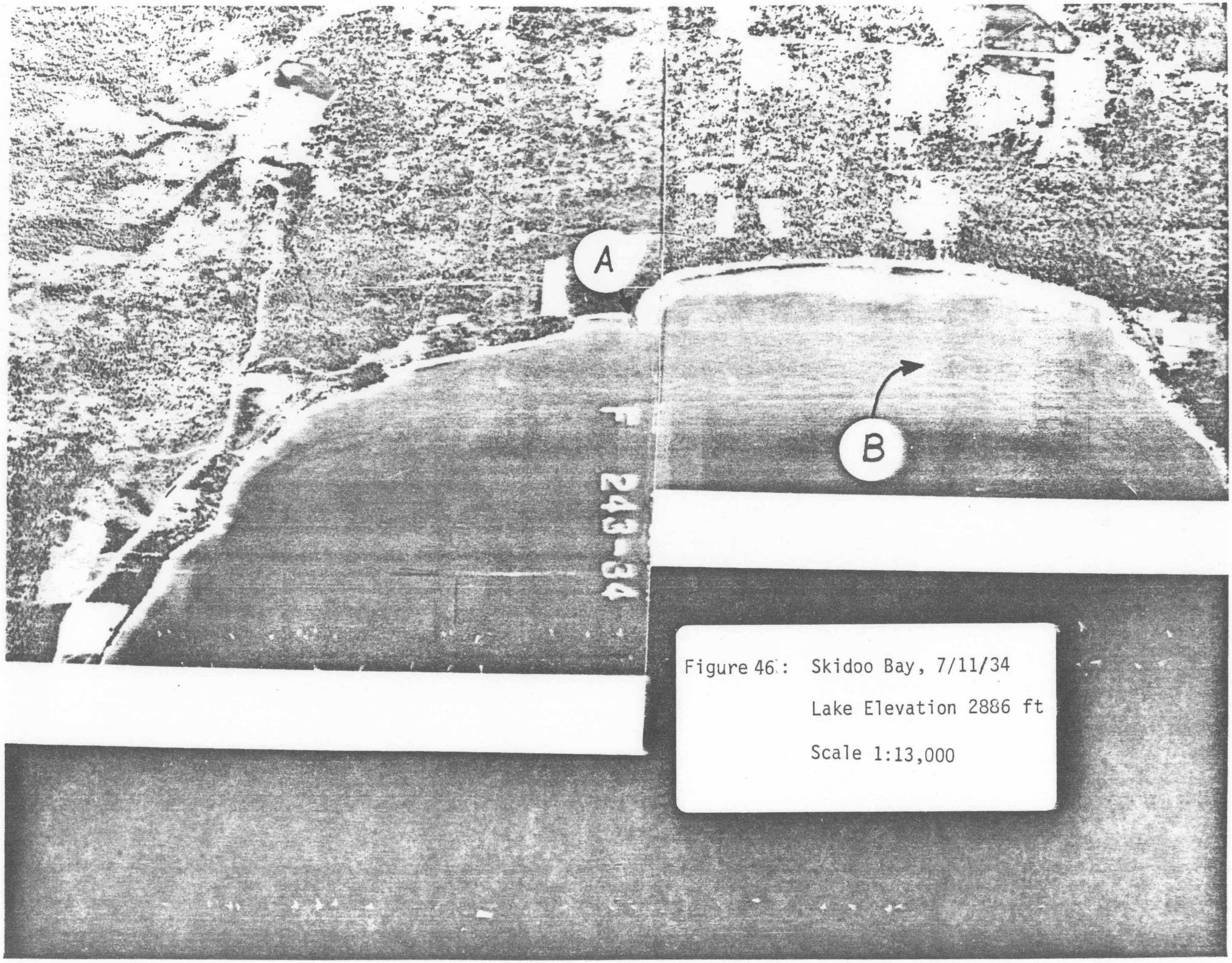
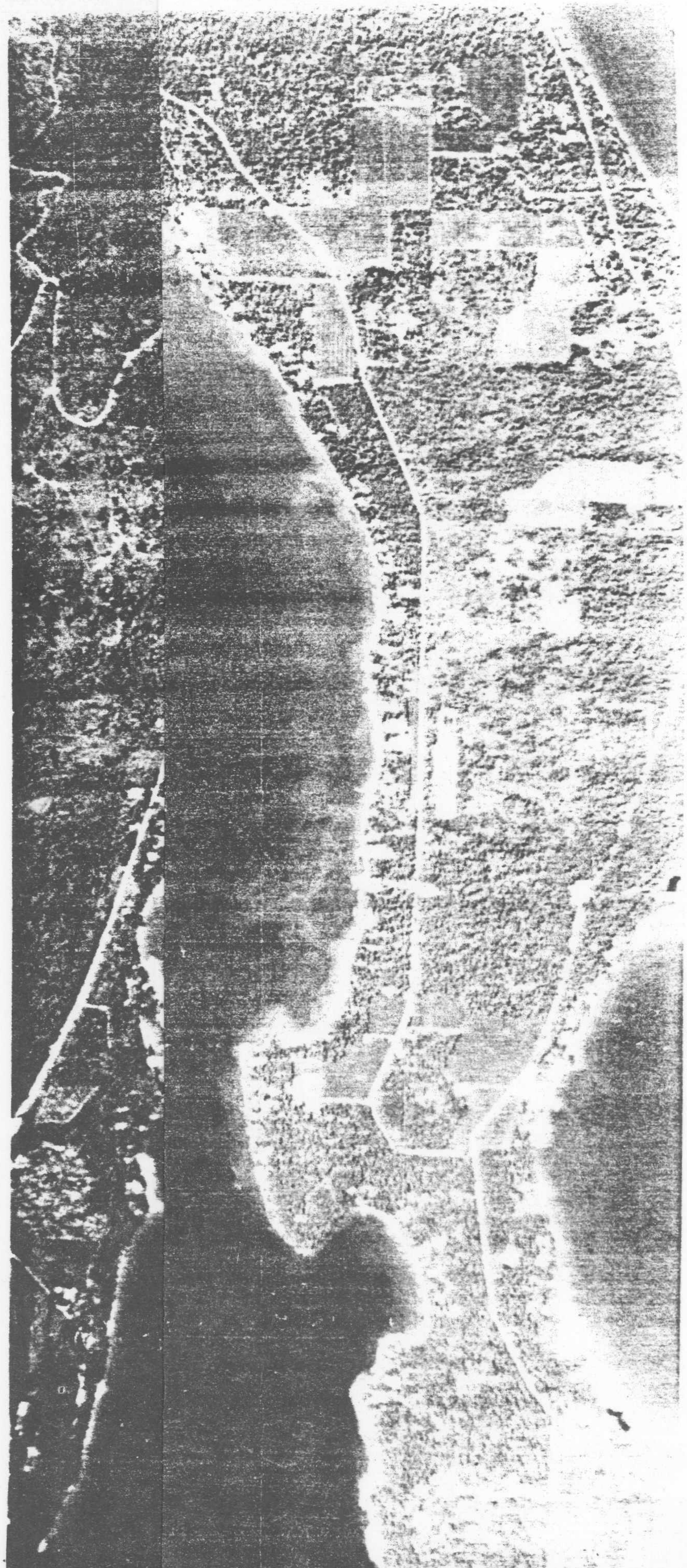


Figure 46: Skidoo Bay, 7/11/34

Lake Elevation 2886 ft

Scale 1:13,000



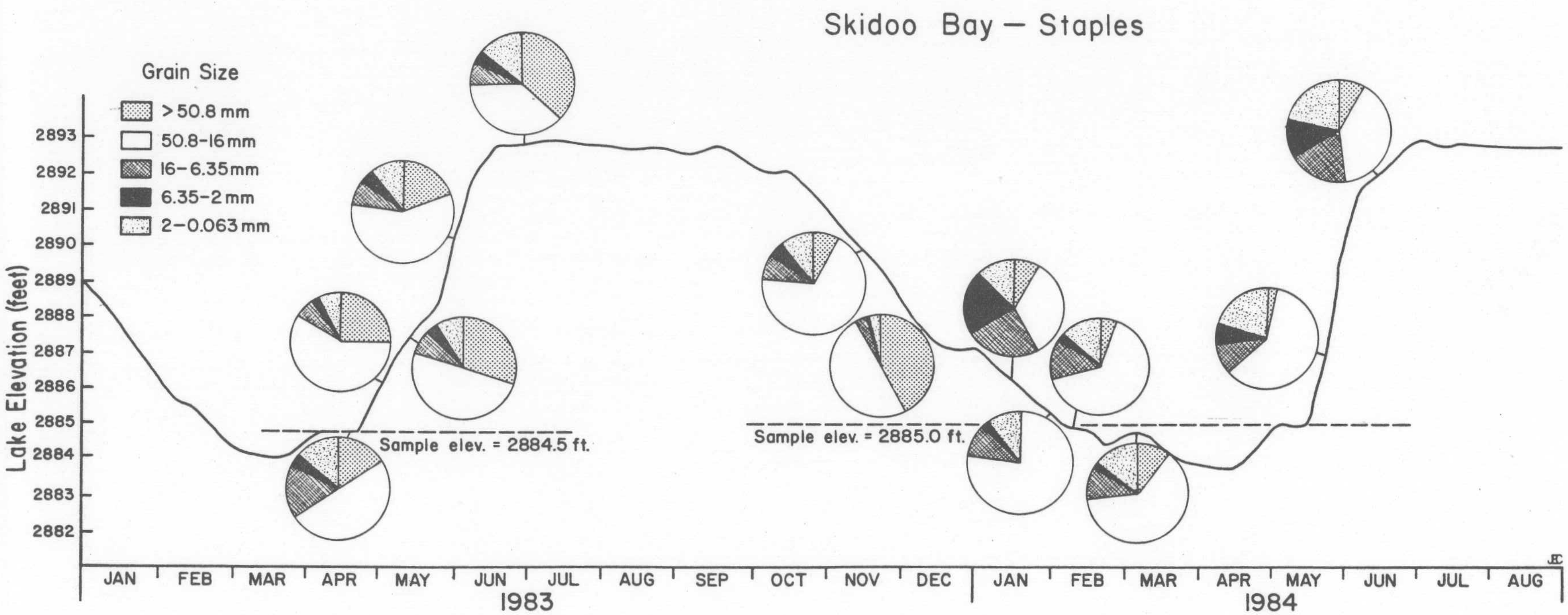


Figure 48: Variation of substrate grain size over time.

Similar dramatic shifts in the grain size continued through the spring and into the summer as the lake rose again. These changes show that waves are reworking the sediment on the beaches of Skidoo Bay, and it is likely that the rapid changes in grain size results from storm waves shifting different grain sizes up and down the beach.

SUMMARY

It is apparent from the data and interpretations presented above that the shorelines of Flathead Lake have changed significantly over the past 50 years. In places where we have a good photographic record (Flathead Lake delta, Point Caroline and the inlet of the Swan River) those changes are seen to occur most rapidly after the construction of Kerr Dam. In 1934 and 1937 photographs, shorelines are dominated by depositional features--bars, spits, broad beaches. By 1955, nearly all the shoreline sites examined have transformed into areas of active erosion and redeposition. Bars and spits have been destroyed, beaches have narrowed, and bays deepened. These processes continue through 1981, but appear to slow significantly. In many places along the shoreline, it appears that the beaches have started to approach a new equilibrium--new spits and bars developing at higher elevations. Shoreline retreat appears to continue, but at a lower rate than immediately following the raise in lake elevation. Again, this is what would be expected for a dynamic wave system readjusting to increased lake elevations. The immediate response of the shoreline to increased wave energy would be to erode and retreat in some areas and outbuild in others. As the sediment was moved lakeward, building bars and covering older beach deposits, the beach would begin to reach an equilibrium profile with the new set of wave dynamics. It appears that the most rapid modification probably occurred during the first 20 years following the raised lake elevations. Since that time the shoreline is slowly approaching a new equilibrium, responding to fall and winter storm waves and disruption of sediment transport by docks. It is extremely unlikely that the modifications seen since 1937 would have occurred without raising the lake level. The pre-1938 shoreline was stable and beaches well developed. Although the details of the destruction of that equilibrium cannot be deciphered from aerial photographs, dramatic changes in beach morphology and dynamics can be seen. This suggests that raising of the elevation of Flathead Lake has had a major impact on beach and shoreline dynamics, which are yet to reach a new equilibrium.

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