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A model of groundwater response to reservoir management and the implications for kokanee salmon spawning Flathead Lake Montana

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A Model of Groundwater Response to Reservoir Management and the Implications for Kokanee Salmon Spawning, Flathead Lake, Montana

by

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Groundwater is known to attract spawning kokanee at Flathead Lake and is hypothesized to extend the survival of kokanee eggs during Kerr dam's winter drawdown of the lake. The goal of the study is to test this hypothesis and determine the extent of the mitigating influence of groundwater.

The hydrogeologic response to the lake drawdown is described from two field seasons at the spawning sites. Field measurements of head and hydraulic conductivity are used to calibrate a finite difference, transient flow simulation of water table response to lake drawdown. The model is used to simulate the response to the various patterns of lake drawdown from 1951 to 1984. The period of dewatering of the spawning area is determined for each of these years. The historical periods of dewatering may be compared with experimentally determined survival rates of dewatered kokanee eggs.

There are three hydrogeologically distinct types of spawning sites at Flathead Lake. They are characterized by (1) a consistently high water table (2) a high water table which responds to lake drawdown and (3) a low-gradient water table. The second type is chosen for modeling since its potential for wetting the spawning redds is most dependent on on the dam operation.

In the simulation of the historic period, groundwater remains within the depth of the redds an average of 30 percent of the time that the lake is down. This is an average; the simulation results show the redds completely dewatered between 1953-1958 and from 1977 to the present at the second type of spawning site. Groundwater can be a mitigating influence at these sites but it is dependent on the water level being drawn down slowly over the elevations at which most of the fish spawn.

ACKNOWLEDGEMENTS

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Chapter 1

INTRODUCTION

Although they are not a native species, kokanee salmon (*Oncorhynchus nerka*) have lived in Flathead Lake for most of this century and have been a popular sport fish for the past fifty years. Currently, they account for ninety-two percent of the catch in the lake (Decker-Hess and Clancey, 1984). The overall population of the fish, however, seems to be dwindling. The concensus among fishermen who have been snagging salmon since the 1930's is that the number of spawning salmon along the lakeshore began to decline in the late 1960's (Decker-Hess and Clancey, 1984). Throughout the 1950's and 1960's, salmon were plentiful and everyone caught their limit. By the late 1970's, however, it was much more difficult to snag one's limit along the shoreline. The observed decline in the salmon population in the late 1960's is further substantiated by the increasing size of the fish. Theory holds that there is an inverse relationship between average size and population density as a result of intraspecific competition (Foerster, 1944). Thus, the smaller the population of kokanee in the lake, the larger the size of the individual fish. The size of kokanee in Flathead Lake has been steadily increasing since the late 1960's (Decker-Hess and Clancey, 1984). Presumably then, the fishermen are right.

The Montana Department of Fish, Wildlife and Parks is undertaking studies to determine why the population is declining. They are studying the spawning fish, the environmental conditions during incubation of the eggs and the emergence of the young fry into the lake. They have noticed that while thirty spawning areas were identified along the lakeshore in the early 1950's only about fifteen of them are used now (Decker-Hess and Clancey, 1984). The current spawning sites have the common trait of influent water, either from a stream or from upwelling groundwater. Groundwater seeps have long been observed as characteristic of salmon and trout spawning areas in the northwest (Benson, 1953; Foerster, 1968; Olsen, 1968; Lewis, 1972). In lab studies, Webster and Eiriksdottir (1976) observed that "when presented with suitable gravel containing an artificially controlled aquifer of about .1% of the area of a circular tank, female trout selected spawning sites that were either in close proximity to the upwelling water or adjacent to it in 21 of 22 trials."

In Flathead Lake, groundwater not only determines where the fish spawn but may also play a significant role in the survival of the salmon eggs. Since Kerr dam was built in 1938, the reproductive success of the shoreline spawners has depended on the dam's method of operation. The dam, located 4.3 miles downstream of the natural lake outlet, has drastically changed the natural pattern of water level fluctuation in the lake (Figure 1). The water level is high (2893 feet elevation) when the fish spawn in November and December but begins to drop in late December. The water level drops continually throughout the winter as water is drafted for energy production and flood control. A minimum pool of 2883 feet is reached by late March or early April. The lake remains low until mid-May when it is refilled rapidly for recreational use in the summer. The result of

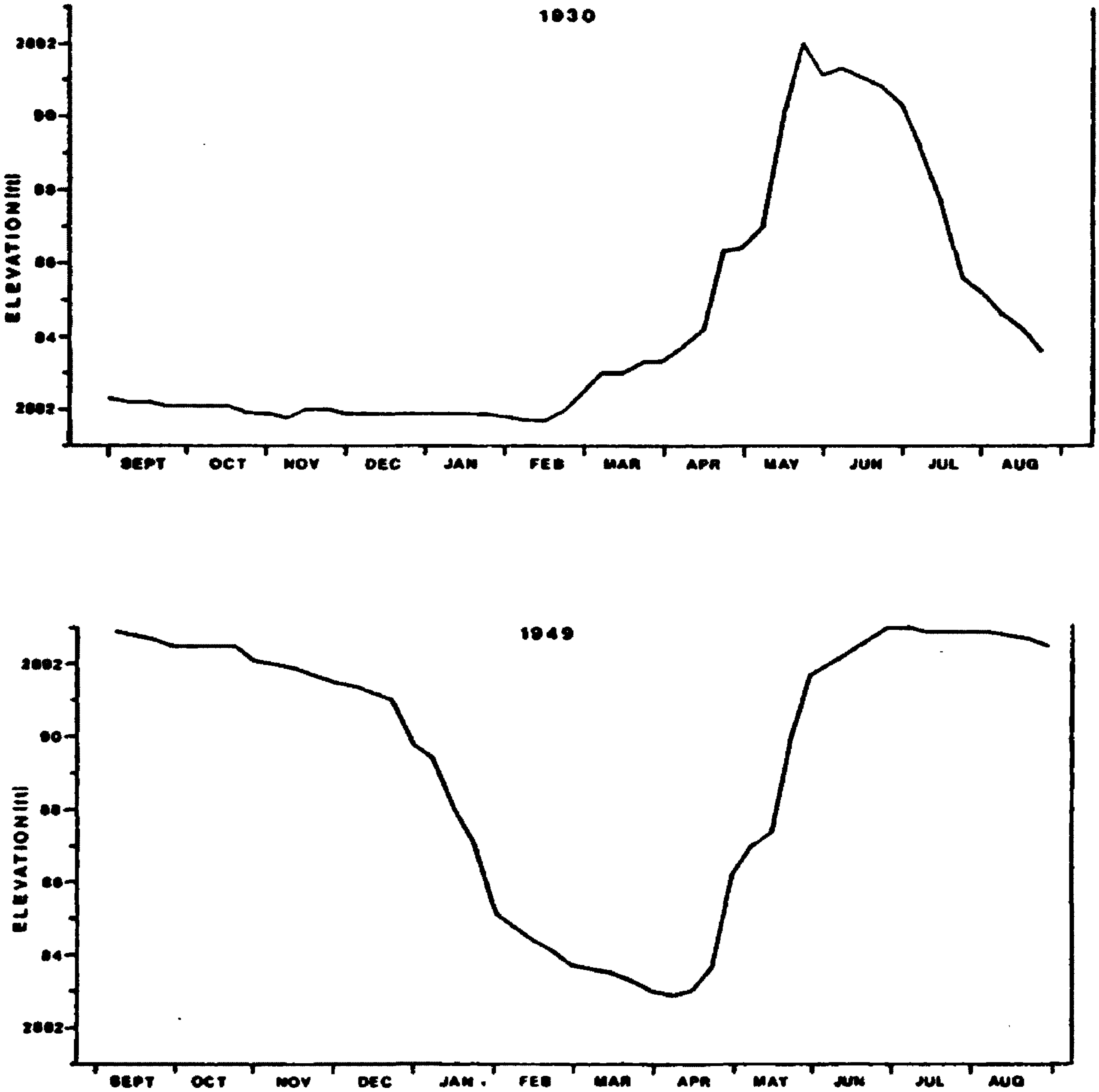


Figure 1: Flathead Lake hydrographs before and after Kerr dam.

this management policy is that many of the redds are dewatered during the critical periods of incubation and emergence. Live eggs and fry are found only in areas which are wetted by groundwater seeps or surface water (Decker-Hess and Clancey, 1984).

Fisheries biologists have recognized the influence of groundwater in maintaining survival in the redds (Becker et al, 1983; Reiser and White, 1983). Very shallow groundwater flow or groundwater seeps could bathe the redds after drawdown and prevent dessication or deleterious temperature fluctuation. Flowing groundwater serves the additional purpose of supplying the eggs or embryos with dissolved oxygen and removing metabolic wastes from the redds. Incubating eggs may benefit from groundwater flow even if the flow is below the base of the redd and does not directly bathe the eggs. In a lab study, Reiser and White (1983) "dewatered" eggs in artificial redds but maintained flowing groundwater 10 cm below the bottoms of the redds. They found that salmonid eggs could tolerate 1 to 5 weeks of this type of dewatering with essentially no effects on hatching success provided that the sediment moisture content was at least 4 percent by weight and the temperature stayed in a reasonable range.

At Flathead Lake, the Montana Department of Fish, Wildlife and Parks has quantified the relationship between egg survival rates and exposure time as a result of dewatering from drawdown of the lake (Decker-Hess and Clancey, 1984). While they believe that groundwater plays a mitigating role during drawdown, the magnitude of that role is unquantified. The purpose of this study is to determine the extent of the influence of groundwater at the spawning sites on the shoreline of

Flathead Lake. The objectives are: (1) to describe the hydrogeology at the existing spawning sites, including the degree to which the water table is affected by lake drawdown (2) to use the field measurements at a chosen site to calibrate a computer model which simulates the groundwater response to lake drawdown over the period from 1951 to 1984, and (3) to determine the yearly and average period of dewatering from a low water table and compare it to dewatering from lake drawdown. Hopefully the results of this study may provide a basis for better management of Kerr dam in terms of a self-sustaining kokanee population.

Chapter 2

HYDROGEOLOGY OF THE SPAWNING SITES

FLATHEAD LAKE

Flathead Lake was formed in Wisconsin time by a lobe of the Cordilleran ice sheet which moved south along the Rocky Mountain Trench. The last stade of this ice sheet deposited the terminal moraine at Polson and the moraine impounded what remains as the largest freshwater lake west of the Mississippi (Alden, 1953). Flathead Lake lies in a basin bounded on the east and west by the Mission and Salish mountains. The bedrock under the entire area is Precambrian, metasedimentary, Belt Supergroup. In several areas around the perimeter of the lake, the metasediments are unconformably overlain by Quaternary glacial till and alluvium.

Few hydrogeologic studies have been done in the vicinity of the lake. Konizeski, et al (1968) described the aquifers in the Kalispell valley to the north and Boettcher (1982) described the Mission and Little Bitterroot valleys to the south, including the southern half of Flathead Lake. Kennett and Curry (1981) investigated high groundwater and seeps at the base of the Polson terminal moraine. There are two primary aquifers around the lake. The Belt rocks contain water in fractures and yield about 10 GPM to wells and occasional springs (Boettcher, 1982). The glacial deposits are more productive, yielding 10 to 1000 GPM, but are unpredictable because of their heterogeneity (Boettcher, 1982; Kennett and Curry, 1981). In terms of recharge, Polson accumulates an average of 15 inches of rainfall a year but the Mission mountains, which serve as the primary recharge area for the east side of the lake, receive about 100 inches, much of it as snow. The hydrographs for wells in the Mission valley show constant or slightly declining water levels from October through June and a rise in the water table in the early summer (Boettcher, 1982).

All but one of the spawning sites investigated in this study are on the east side of the lake and all of them are located in areas of glacial till (Figure 2). The till has been reworked by waves along the shoreline leaving near-shore deposits of unsorted sand, gravel and cobbles.

INSTRUMENTATION AND MEASUREMENTS

During the winters of 1983, 1984 and 1985 the water table at 12 spawning sites was monitored as the lake fell and rose. As the lake receded, 3 to 4 sandpoints (1.5 inch diameter with 1 foot of 80-mesh screen) were driven into the beach gravels at each site. The sceened interval was placed 1 to 3 feet deep. The sandpoints were used for biweekly head measurements and for testing the hydraulic conductivity of the gravel. In addition, four of the sites were outfitted with 4 inch diameter, open-ended wells driven to a depth of 10 to 12 feet, placed near the high water line, and equipped with continuous water level recorders. A complete description of the instrumentation and results can be found in Woessner and Brick (1983 and 1984).

The hydraulic conductivity of the beach sediments was determined

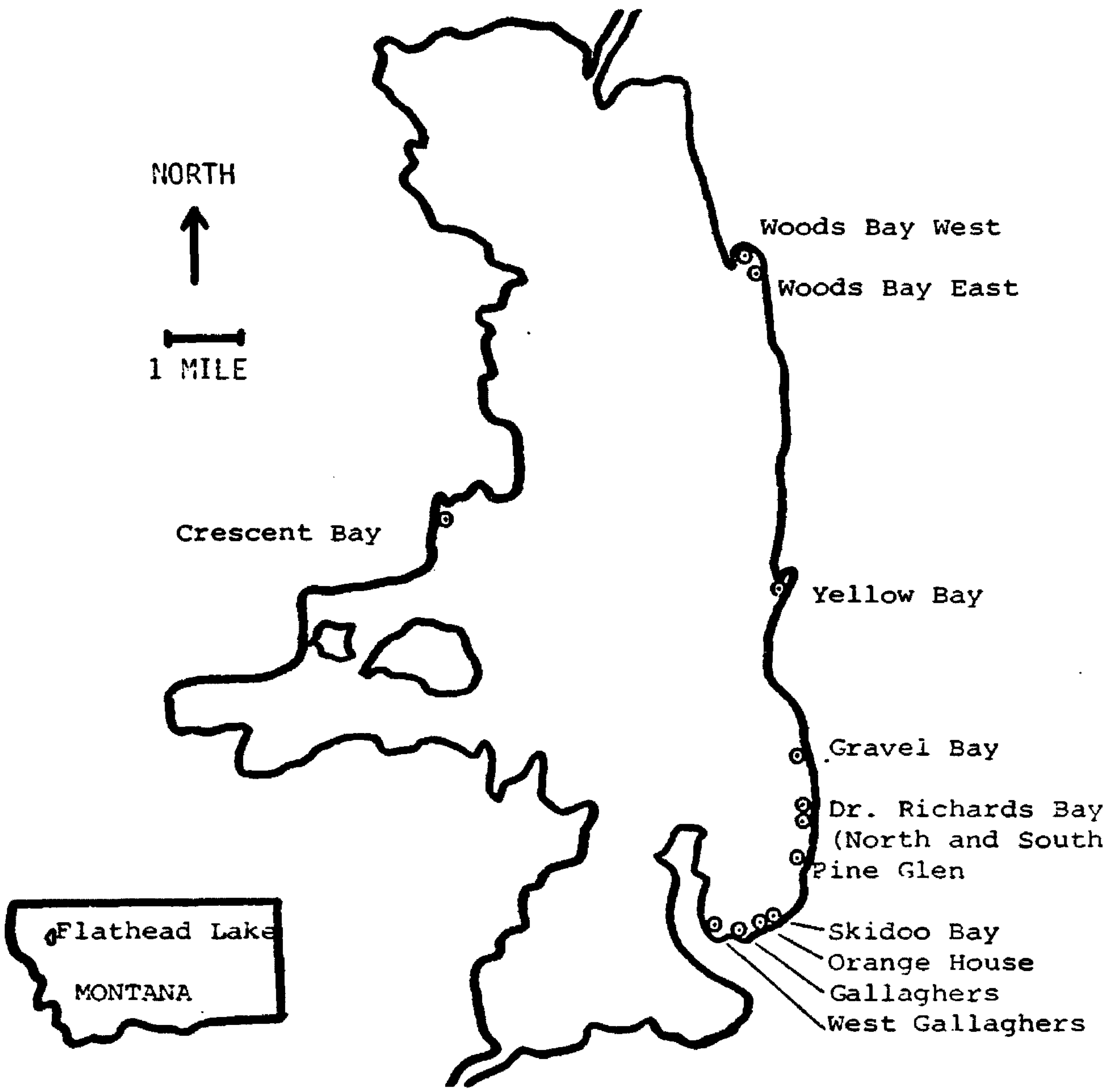


Figure 2: Location of the spawning sites on Flathead Lake.

by a method for sandpoints described by Donnan and Aronovici (1961). The water level in the sandpoint is drawn down by a small, carefully measured amount. The well is then continually pumped to maintain this measured drawdown and the groundwater discharge is recorded. The hydraulic conductivity is determined by the relationship:

$$K = Q / AH \qquad (1)$$

where: Q = discharge from the well

A = a shape function

H = the head drawn down in the well.

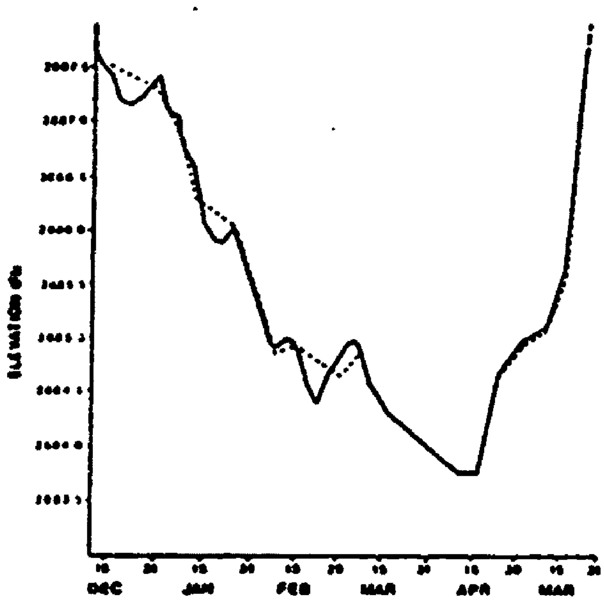
The term A is a constant which is a function of the geometry of the well point. It accounts for distortion of the flow field around the well. I calculated a value of A for the sandpoints using the relationships given by Kadir (1955). The conductivity values for each site are in Table 1.

DESCRIPTION AND CLASSIFICATION

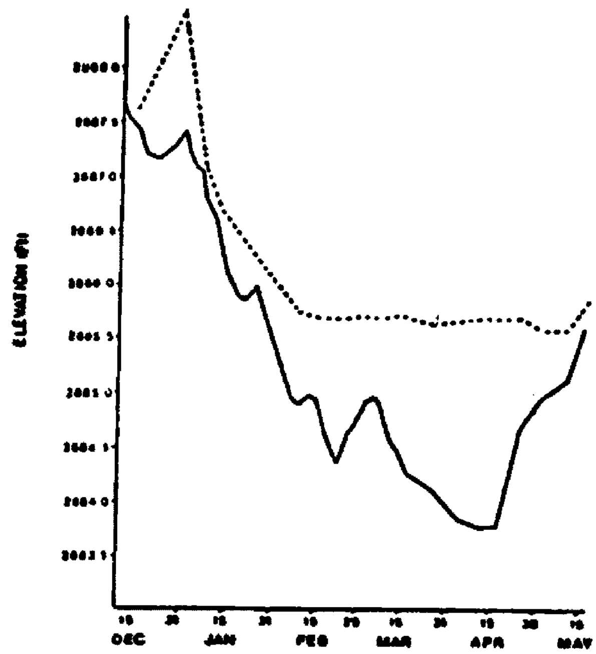
After measuring the hydraulic head at each site during the spawning, incubation and emergence periods, it was soon apparent that the sites could be classified into three, hydrogeologically distinct types. The classification is based on the response of the water table to the drop and rise in lake level. A hydrograph of an example of each type of site is presented in Figure 3. At type A sites, the water table responds virtually instantaneously with the change in lake stage. These sites have an essentially flat gradient in the beach area. The water table at type B sites has a steeper hydraulic gradient. It begins to decline as the lake declines but it doesn't

Table 1: Selected hydraulic conductivity measurements.

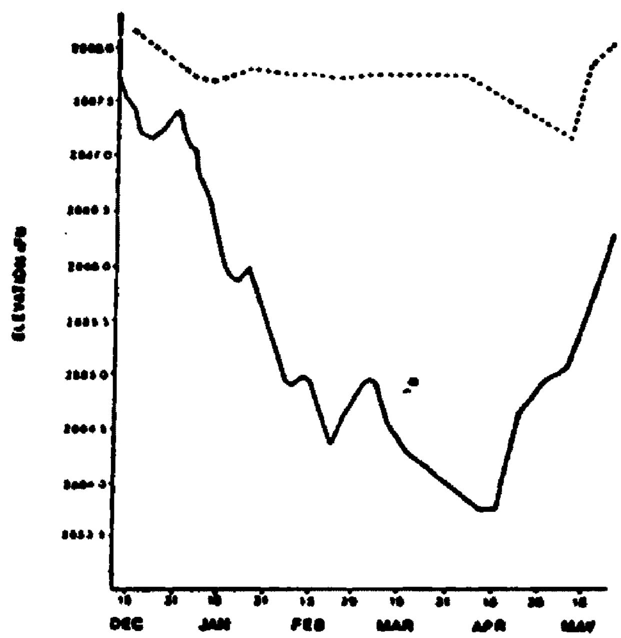
TYPE OF SITE	SITE	WELL #	K in GPD/FT^2
	Pine Glen	PG-2	2607
	Dr. Richards South	DRS-2	4332
A	Gravel Bay	GB-1	1136
	Woods Bay East	WBE-3	4337
	Woods Bay West	WBW-1	3207
	Skidoo Bay	SKB-1	124
		SKB-2	147
		SKB-3A	311
B	Orange House	OH-2	171
		OH-3	65
	Yellow Bay	YB-3	400
	Gallaghers	GAL-2	129
		GAL-3	65
	West Gallaghers	WGAL-1	118
C		WGAL-2	88
	Dr. Richards North	BH-1	171
		BH-3	77
	Crescent Bay	CR-1	35
		CR-2	247



TYPE A: WOODS BAY WEST



TYPE B: YELLOW BAY



TYPE C: DR. RICHARDS BAY NORTH

Figure 3: Hydrographs of the three types of water table response (dotted line) to lake drawdown (solid line).

fall as far or as fast. During the period of the lowest lake level, from February through April, the water table at these sites tends to remain in a steady state. It rises quickly though in May as the lake is being refilled. At type C sites, the water table is virtually independent of lake fluctuations. It remains high regardless of the lake stage. The type C sites all have surface streams which flow into the lake year-round.

The different water table responses can be explained in terms of the hydraulic conductivity and recharge to the aquifer. Hydraulic conductivity is much higher at type A sites than at type B or C sites (Table 1). High conductivity through the beach gravel will result in a flat water table and immediate adjustment of the water table to the lake because water is so readily transmitted through the aquifer. In addition, the type A areas are located in areas with smaller deposits of glacial till, therefore limited storage capacity and lower recharge to the beach. The type B and C sites have lower values of hydraulic conductivity. This means that water is not transmitted as readily and the aquifer will take longer to respond to boundary effects such as a drop or rise in lake level. Type B and C sites also experience higher recharge as a result of more extensive till deposits upshore. The high water table and presence of streams at type C sites indicates the highest relative recharge among the three types of sites.

The hydrogeological distinctions between spawning sites are reflected in the survival rates of the salmon eggs. In 1982-83 and 1983-84, Montana Fish, Wildlife and Parks personnel found that the fish spawned in approximately equal numbers at the three types of sites but that the percentage of egg survival to the eyed stage differed between sites. Table 2 summarizes the findings of Decker-Hess and Clancey (1984).

Table 2: Survival rates of kokanee eggs at Flathead Lake, 1983-84.

TYPE OF SITE	NUMBER OF REDDS EXPOSED BY LAKE DRAWDOWN	1983-84 SURVIVAL RATE
A	108	7 %
B	109	24-65 %
C	137	74 %

Type C sites are clearly the best sites for spawning and type A sites are the worst. While not quite as good as type C sites, type B sites still provide a viable spawning ground in which groundwater seems to compensate for the exposure from the lake. Since the survival of the salmon eggs may be dependent on the groundwater regime as well as the management of the lake, this is the type of site on which this study focuses. Type B sites are also suited to predictive modeling since the water table changes at a different rate than the lake. The type B site chosen for modeling is described next.

THE MODELING STUDY SITE

Skidoo Bay is a large, shallow bay at the southeast end of the lake and the study site is at the southeast end of the bay (Figure 2). On the shore adjacent to the bay, a wedge of glacial till overlies

Precambrian metasediments of the Belt group. According to driller's logs, the till is 50 to 400 feet thick and contains discontinuous lenses of sand, gravel and clay. The till extends about three quarters of a mile to the southeast where it abuts the steep slopes and bedrock outcrops of the northern end of the Mission range. Residents along the shore of Skidoo Bay pump groundwater from sand and gravel lenses in the till and from the fractured bedrock below it. The water-producing horizons in the till are confined or partially confined by the clay lenses. However, the water which flows through the beach and into the lake is unconfined.

The beach is composed of an upper sand and gravel unit and a lower sand unit (Figure 4). Unsorted, well-rounded gravel and fine to coarse sand make up the top 1 to 2 feet of the beach. The gravel at the surface is sorted by waves into berms which are left behind as the lake retreats. Below the sand and gravel there is a layer of fine to medium grained, well-sorted sand. The thickness of this unit is unknown. The upper sand and gravel layer thins toward the lake and the sand horizon is exposed at the surface near the lower edge of the beach when the lake is in the lowest stage.

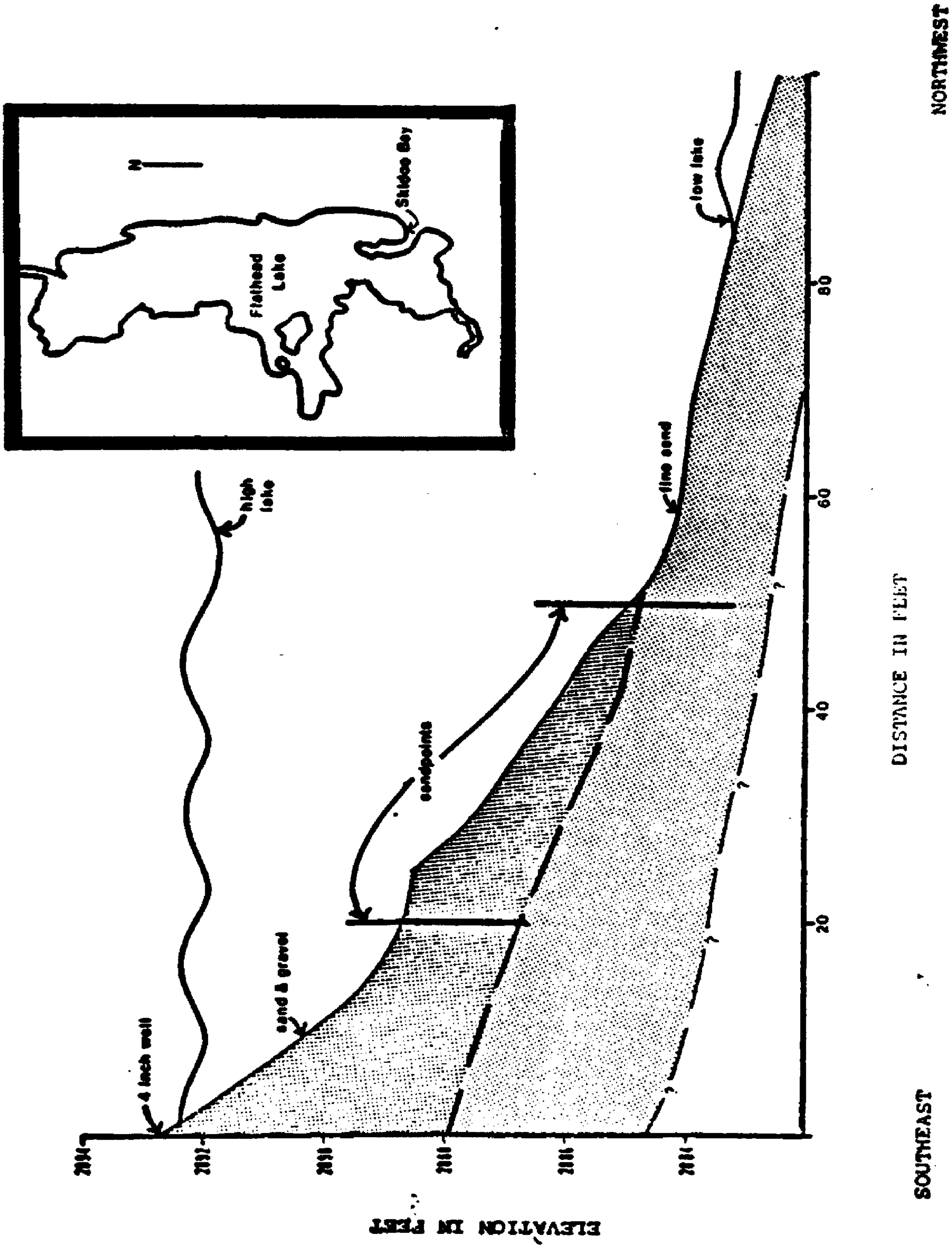


Figure 4: Cross-section of the Skidoo Bay study site.

Chapter 3

METHODS

THE MODEL

The model used in this study was developed by Prickett and Lonnquist (1971) and Prickett, Naymik and Lonnquist (1981). The actual software used is the more recent version of the model mentioned above. The model can simulate two dimensional, steady or transient flow in a heterogeneous, water table, artesian or leaky artesian aquifer. The model can also be used to predict the movement of groundwater contaminants and to predict the effects of time-varying pumping or injection.

The model is based on the partial differential equation which describes transient, two dimensional flow of groundwater (Jacob, 1950).

$$\frac{\partial}{\partial x}(K_x b)\frac{\partial h}{\partial x} + \frac{\partial}{\partial y}(K_y b)\frac{\partial h}{\partial y} = S\frac{\partial h}{\partial t} + Q \qquad (2)$$

where: Kx = hydraulic conductivity in the x direction

Ky = hydraulic conductivity in the y direction

S = storage coefficient of the aquifer

h = hydraulic head above the bottom of the aquifer

b = saturated thickness of the aquifer

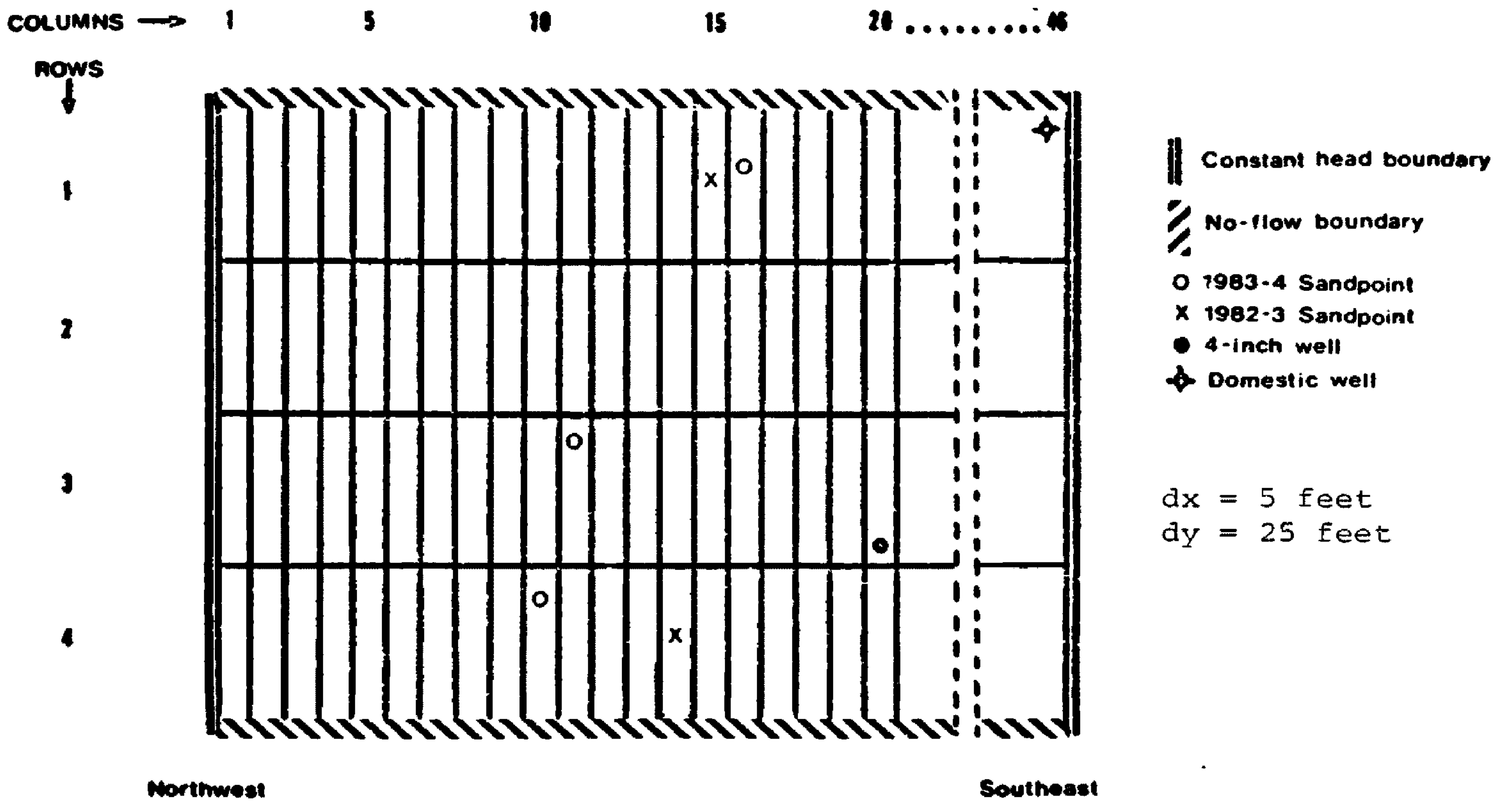
t = time

Q = recharge or discharge

The method of finite differences is used to approximate a solution for equation (2). In the finite difference solution, the hydrogeologic properties of the aquifer are discretized into a finite number of blocks in a grid. A finite difference equation, which is an algebraic approximation of equation (2), is formulated for a single node on each block. Thus for each time step, if there are twenty nodes, twenty simultaneous finite difference equations are solved to determine twenty values of head, one at each node. The set of simultaneous equations is solved by the modified iterative alternating direction implicit (MIADI) algorithm described by Prickett and Lonnquist (1971). The calculated heads are then used as initial conditions for the next time step and the process is repeated until the end of the given time period.

The scenario at Skidoo bay is modeled as a transient flow situation with time steps of five days. The first five time steps are run with a constant lake level to allow the water table to reach equilibrium. The rest of the simulation then uses the actual lake elevation every five days to determine the boundary for the calculation of new hydraulic heads. The simulation begins on October 5 of a given year and proceeds until the end of May.

To do this, I had to modify the model slightly to allow for a moveable constant head boundary. The added subroutine (Appendix A) allows the boundary representing Flathead Lake to move right or left as the lake level rises or falls. It assigns an elevation to the nodes in each column of the twenty columns which represent the beach (Figure 5). The node spacing between the beach columns is a uniform five feet so the elevation at a given node is dependent on the slope profile of the beach. During the simulation, as the lake level begins



COLUMN ELEVATIONS

Column	Elevation (feet)	Column	Elevation (feet)
1	2882.80	11	2885.65
2	2883.00	12	2886.20
3	2883.20	13	2886.30
4	2883.40	14	2887.40
5	2883.60	15	2888.50
6	2883.80	16	2888.75
7	2884.00	17	2889.20
8	2884.15	18	2890.25
9	2884.30	19	2891.50
10	2884.74	20	2892.80
		46	3010.00

Figure 5: Modeling grid and boundary conditions.

to drop with successive time steps, the elevation assigned to the node adjacent to the constant head boundary is checked until the actual lake level is halfway between the two values. At that point, the constant head boundary is shifted to the adjacent node. The node which was formerly the constant head boundary is now a regular node in the aquifer. Because the nodes are five feet apart, the simulated lake rises and falls in steps rather than smoothly and uniformly as it does in the real setting. The simulated water table responds by rising and falling in steps also. This needs to be considered when interpreting the results. Fitting a smooth line to the stepped curve produced by the model should approximate a more realistic response.

SKIDOO BAY PARAMETERS AND BOUNDARIES

The grid and boundary conditions for Skidoo bay are illustrated in Figure 5. The node spacing in the north-south direction is 25 feet over the entire grid. In the east-west direction. it is 5 feet for the 20 nodes on the beach and increases to 200 feet at node 46 on the southeastern (right-hand) boundary. The northern and southern boundaries, which generously exceed the limits of the spawning area, are parallel to groundwater flow and are thus designated as no-flow boundaries. The eastern boundary is determined by a topographical divide and is assigned as a constant head boundary to account for recharge to the aquifer. The value of head assigned to this boundary is based on field measurements from a domestic well completed in the till and located near the boundary. The position of this recharge boundary is so far removed from the area of interest on the beach that it essentially represents an infinite aquifer. The western boundary, previously described, is a constant head boundary and represents the elevation of Flathead lake.

The model requires that values of hydraulic conductivity, aquifer thickness, storage coefficient and initial head be assigned to each node (Table 3). These hydrogeologic parameters may either be determined in the field or estimated. Usually, they are imperfectly known and therefore adjusted during the calibration phase of the modeling in order to match the modeled results with real data. The source of the parameters used in this model is described next.

As previously discussed in this paper, the hydraulic conductivity of the beach deposits was determined by the method of Donnan and Aronovici (1961) and Kadir (1955). I placed a zone of higher hydraulic conductivity in the first nine columns of the grid. This is warranted from several observations. First, the conductivity measured in sandpoint 3A, located in this zone closest to the lake, is double that measured in the other sandpoints. Sandpoint 3A was screened in the well-sorted sand which underlies the unsorted sand and gravel. The other sandpoints were screened in the sand and gravel (see Figure 4). Although the sand and gravel deposit contains coarser material, and conductivity can increase with increased particle size, Masch and Denny (1966) determined that the hydraulic conductivity will increase with a decrease in the standard deviation of the particle size. The zone of high hydraulic conductivity adjacent to the lake also proved to be necessary in order to calibrate the model. The second zone of

Table 3: Model parameters for Skidoo Bay.

DEFAULT PARAMETERS:

Storage coefficient	0.1
Initial head	210 ft
Hydraulic conductivity	100 gpd/ft^2
Thickness	210 ft

ZONE PARAMETERS:

Columns 1-9: Hydraulic conductivity	240 gpd/ft^2
Columns 10-20: Hydraulic conductivity	120 gpd/ft^2
Columns 1-15: Thickness	200 ft
Constant head boundary at column 46 and at the elevation of the lake: Storage coefficient	10^{30}

hydraulic conductivity extends from halfway up the beach to the high water mark and is defined by the conductivity values measured in sandpoints 1 and 2. The rest of the aquifer (upland from the beach) is assigned a conductivity which is estimated from the driller's log of an aquifer test in the domestic well near the eastern boundary of the model.

The thickness of the aquifer is also estimated from driller's logs of several wells in the vicinity. The thickness of the glacial till appears to be erratic and probably reflects a complex topography on the underlying Belt rocks. I used an average, overall thickness of 220 feet except on the beach where I narrowed it slightly to 210 feet. This decrease in thickness was a necessary "fine-tuning" in the final calibration of the model.

All of the parameters discussed above, along with the initial value of hydraulic head at each node, are compiled into the input file for the model. The modification allowing for the moveable lake boundary requires two additional input files. One contains the actual lake elevations for a given year at five day intervals and the other contains the original beach elevations of the first twenty nodes of the model which are used to reassign the values as the lake rises.

CALIBRATION AND VERIFICATION OF THE MODEL

The parameters discussed above were first determined from field measurements or observations but the final values used in the model were determined after the process of calibration. Using the minimum lake level, I ran the model to a steady state solution of the water table and compared the computed heads with actual heads measured in 1983-84. The final model parameters which yield the best match to history are easily within the range of uncertainty of the measured values.

After the steady state calibration, I ran the model under transient flow conditions and verified it with two sets of historic lake and groundwater head data. The goal of verification is to demonstrate that the model can reproduce some historical event other than the calibration scenario (Wang and Anderson, 1982). I ran the 1983-84 data first and made small adjustments to obtain a good history match under transient conditions. At the location of one of the sandpoints, the modeled results deviate from the head data by no more than two inches (Figure 6). The 1982-83 data further verifies the validity of the model. The initial parameters were not adjusted at all for this run and the modeled results are off by a maximum of three and a half inches at the location of the sandpoint (Figure 7).

ANALYSIS OF SENSITIVITY

The method of adjusting initial parameters until the computed heads agree with field data could lead to spurious conclusions because the solution may not be unique. For example, Gillham and Farvolden (1974) examined the sensitivity of the computed hydraulic head to changes in the hydraulic conductivity and found that various distributions of hydraulic conductivity would result in the same head

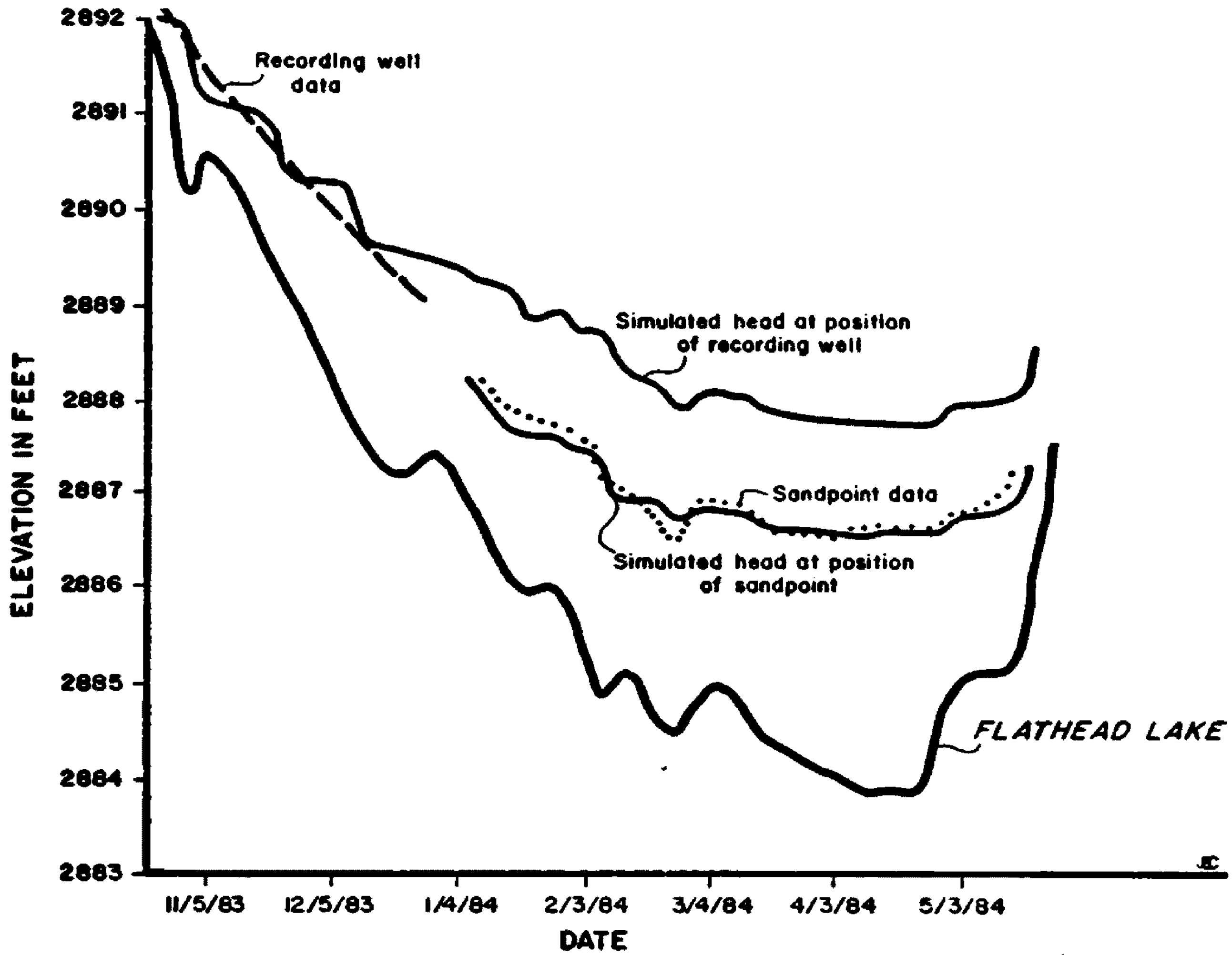


Figure 6: Calibration of the model with 1983-84 data.

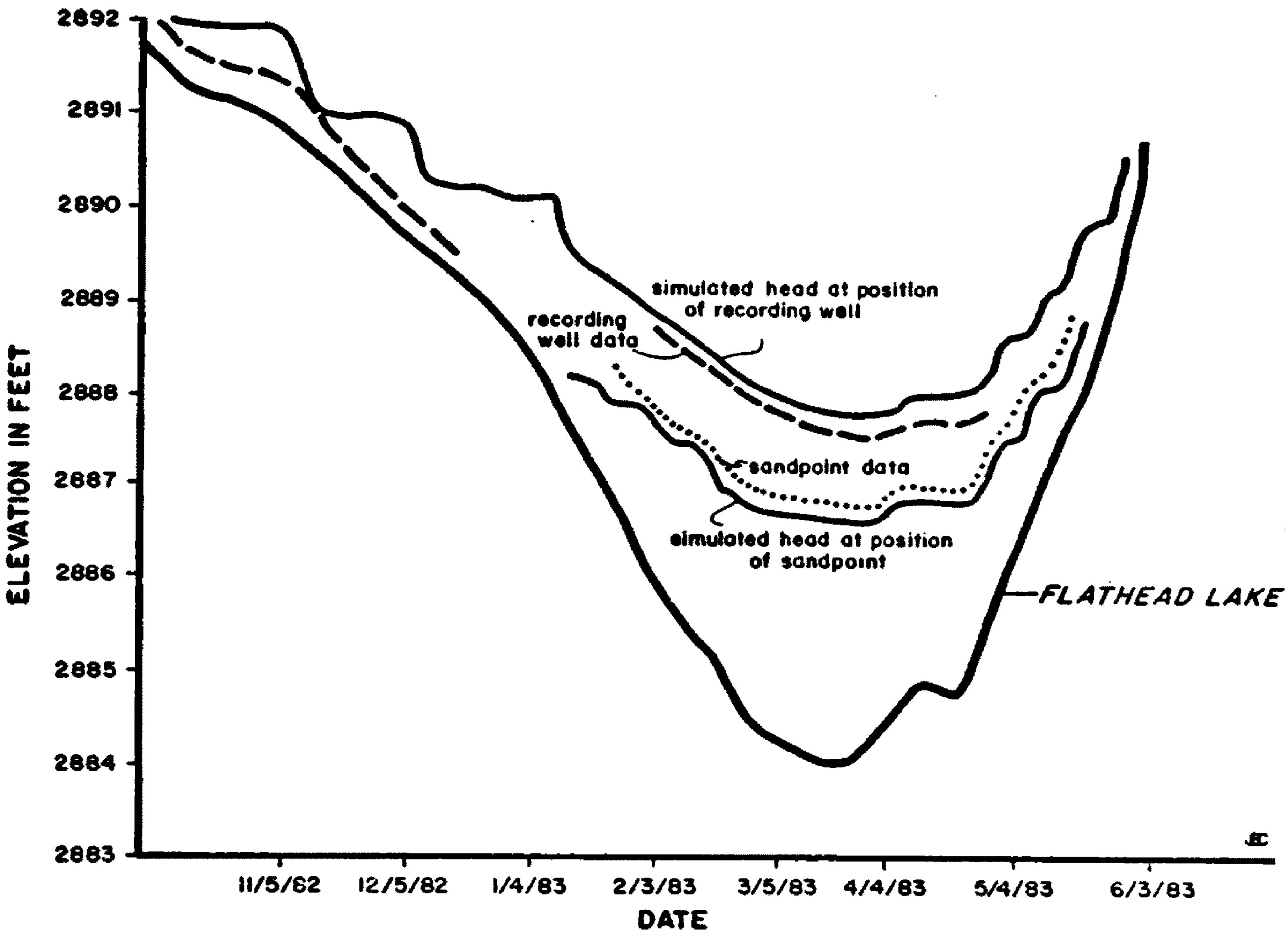


Figure 7: Verification of the model with 1982-83 data.

distribution. Another potential source of error could lie in applying local measurements to the entire aquifer. In a unit of unconsolidated material such as glacial till, the hydraulic conductivity can vary by several orders of magnitude (Norris, 1963). A local measurement could be entirely erroneous for the bulk of the aquifer (Gillham and Farvolden, 1974). Thus it is important to know how changes in the initial variables will affect the modeled values of head. This is the purpose of a sensitivity analysis.

At Skidoo Bay, the initial parameters are reasonably well established from field data but are still imperfectly known since they could not be measured at every node on the grid. The hydraulic conductivity is measured at three points on the beach and at one point for the rest of the aquifer. The value of recharge is inferred from one point and the thickness is averaged from three points. The value of specific yield is only estimated. In the sensitivity study, these parameters were increased or decreased, one at a time, by a given percentage. Since the area of interest is on the beach, only the beach nodes were examined for a percentage change in hydraulic head. The manipulations to the initial parameters and the resultant change to values of head are listed in Table 4.

The range of percentages listed for the head variations in Table 4 reflects the fact that the influence of the given parameter becomes more pronounced with distance from the constant head boundary of the lake. The smaller value is from the node adjacent to the lake and the larger value is from the node at the high water line.

Although all the percentage changes in head are small and appear

Table 4: Results of the sensitivity analysis.

PARAMETER	% CHANGE TO PARAMETER	RESULTANT % CHANGE IN HEAD (NODE 7-NODE 20)	ABSOLUTE CHANGE IN HEAD (FEET) (NODE 7-NODE 20)
Hydraulic Conductivity	+50 %	-.01 to -.19 %	.01 to .15
	-90 %	+.31 to +6.07 %	.26 to 5.68
	-50 % (on the beach)	+.20 to +1.02 %	.17 to .78
Recharge Boundary	-10 %	-.07 to -.66 %	.06 to .58
Thickness of the aquifer	-10 %	+.12 to +.54 %	.10 to .31
Storage Coefficient	-90 %	-.04 to -.33 %	.03 to .29

insignificant, it is more pertinent to look at absolute differences in head. Since the goal of the model is to determine when the water table falls below the base of the redds, a difference of 6 inches is important.

The value assigned to hydraulic conductivity becomes important only on an order-of-magnitude scale. Doubling the initial value did not significantly influence the results but a decrease of 90 percent changed the head by 5 feet or more. Removing the zone of high conductivity on the beach made a significant but not drastic change in head. This zone is easily justified by field measurements and proved to be convenient in the "fine-tuning" of the simulation.

The aquifer as I model it is heterogeneous and isotropic. The heterogeneous zones all have values of hydraulic conductivity within the same order of magnitude. The sensitivity analysis suggests that this might not be very different from modeling a homogeneous aquifer since the difference in head is minimal after the conductivity is doubled. Even though the hydraulic conductivity of glacial till can vary widely, in a basin-wide simulation groundwater motion may be treated as unconfined flow through a homogeneous medium (Toth, 1963). The base of the aquifer may either be an impermeable layer or a layer with hydraulic conductivity an order of magnitude lower than the overlying aquifer (Freeze and Witherspoon, 1967). Thus, order of magnitude changes are significant but smaller changes probably are not. On a gross, basin-wide scale the heterogeneity of the model is probably not necessary, but on the smaller scale of the beach it becomes more important.

Modifications to the recharge boundary and the thickness were based on what might realistically be expected from field observations. In both cases, the effect on the simulated hydraulic head does not appear to be biologically important in terms of redd viability. Likewise, an order of magnitude decrease in the storage coefficient, which represents the lower limit of reasonable values for this parameter, produces a very minor change in head. Thus, in terms of the initial parameters, the head values in the spawning area, as they would potentially affect a redd, are sensitive only to an order of magnitude change in the hydraulic conductivity.

Chapter 4

RESULTS

At the end of the simulation, the program prints the water level elevation at all nodes on the grid for each five day time increment. In all of the simulations, groundwater flow remains perpendicular to the constant head boundaries and parallel to the no-flow boundaries. Although modeled in two dimensions, this is essentially a one-dimensional problem which therefore results in a one-dimensional solution.

The elevations between 2884.00 feet and 2888.50 feet cover about 90 percent of the total spawning area (Decker-Hess and Clancey, 1984). Below 2884.00 feet the lake covers the beach most years and above 2888.50 feet there is very little spawning as well as very little hope for the few eggs which are deposited there. Most of the following discussion focuses on the interval between 2884.00 and 2888.50 feet.

A summary of the results of the simulation from 1951 to 1984 is presented in Figures 8-14 and the actual tabulations can be found in Appendix B. The elevations on Figures 8-14 represent adjacent nodes and are thus five feet apart horizontally except for 2884.00 feet and 2884.75 feet. These elevations are three nodes (fifteen feet) apart. To construct these figures, I used the simulation results to determine how long the lake exposed a given gravel elevation between October 1 and May 31 of the designated year. The total height of each bar represents the exposure time from the lake. I also recorded the number of days that the groundwater fell below the redd depth of six

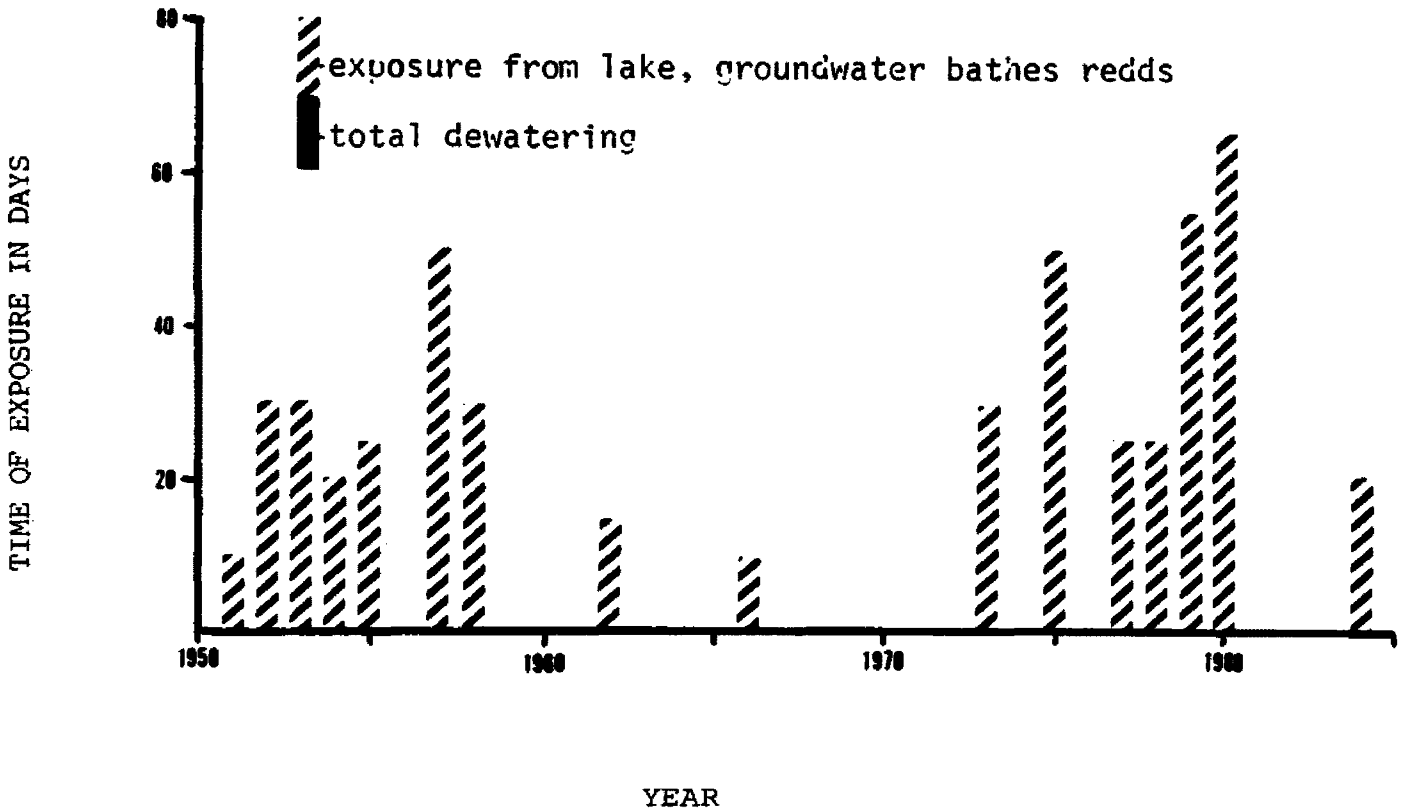


Figure 8: Simulated redd exposure from 1951-1984 at 2884.00 feet.

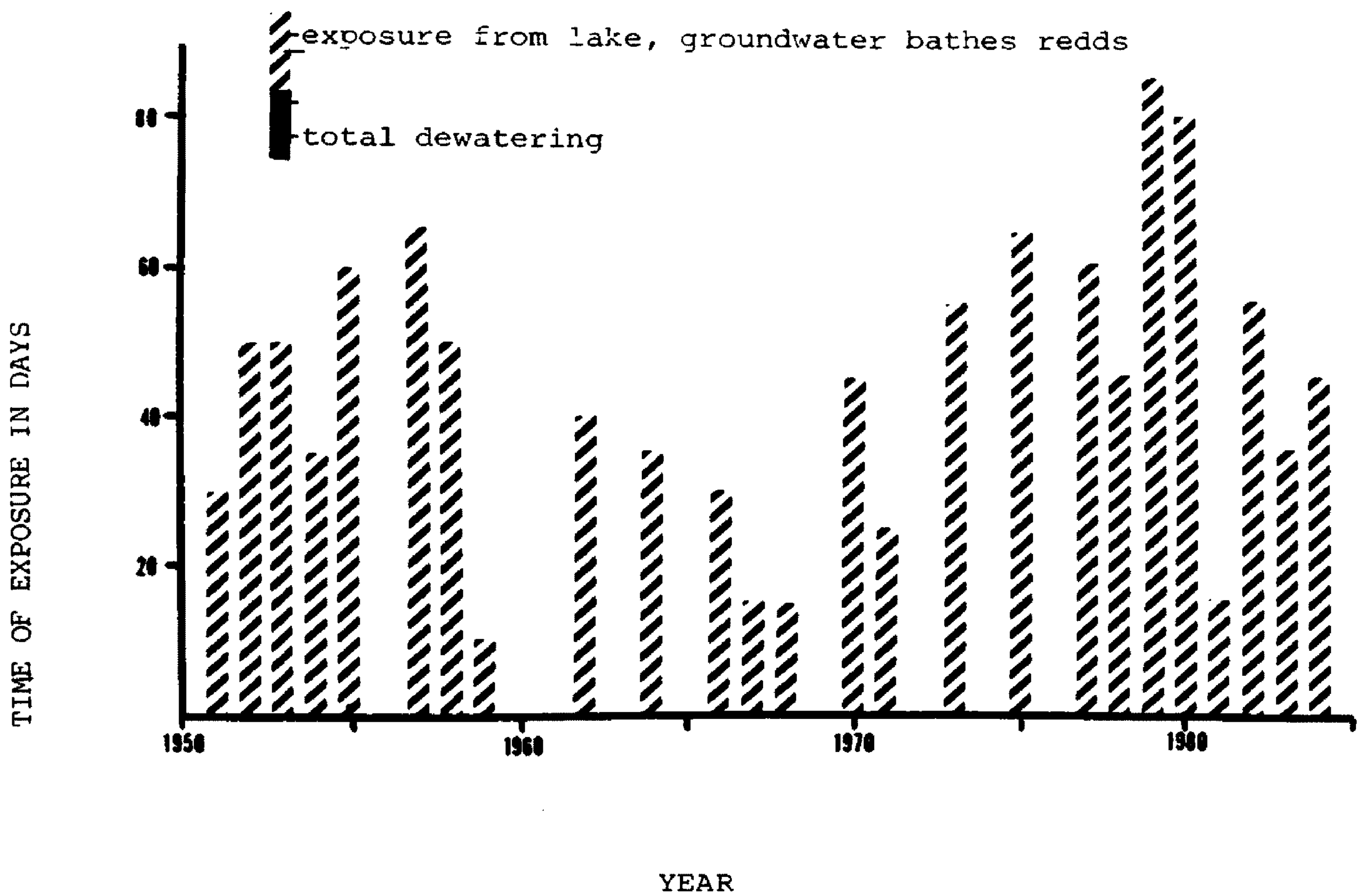


Figure 9: Simulated redd exposure from 1951-1984 at 2884.75 feet.

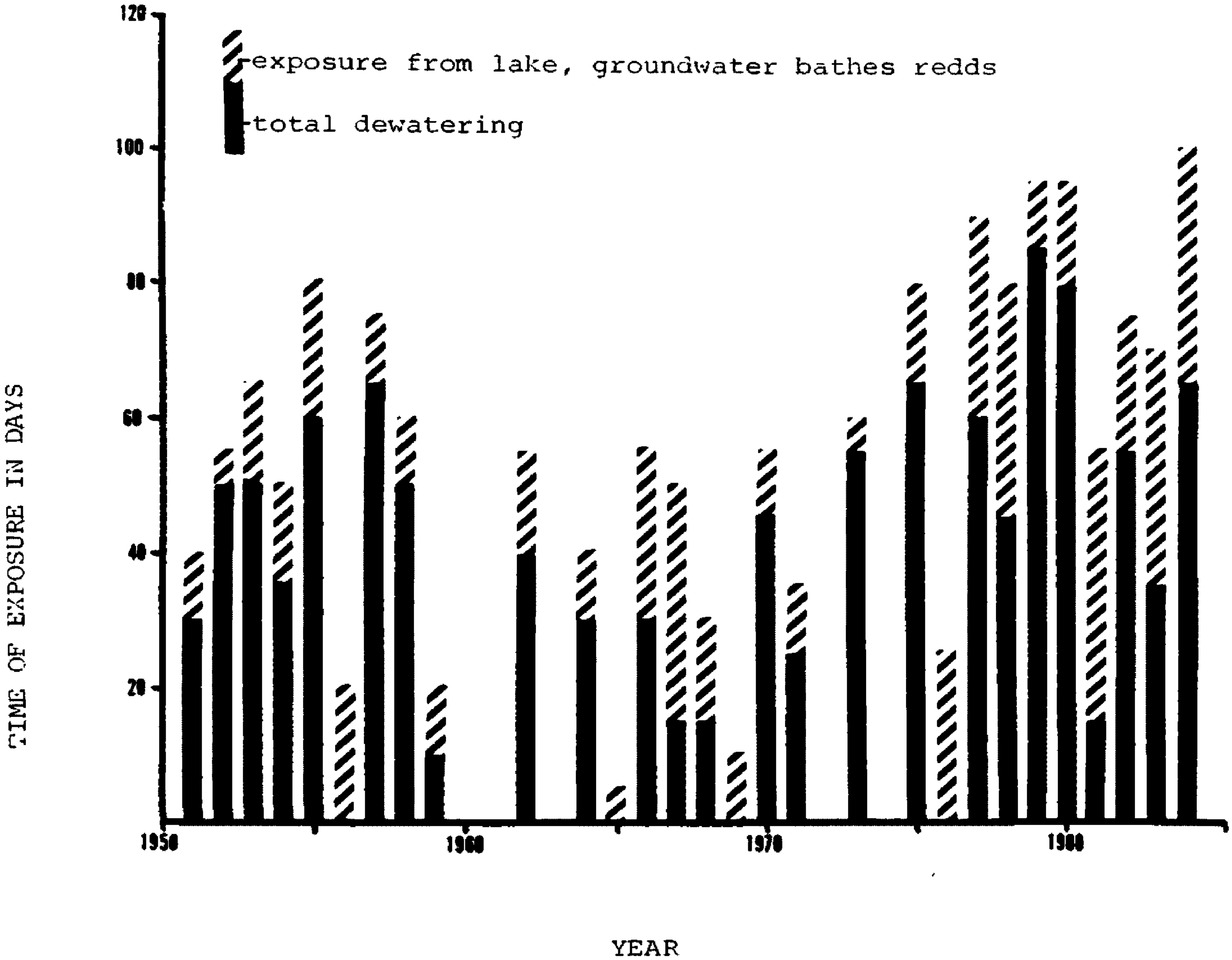


Figure 10: Simulated redd exposure from 1951-1984 at 2885.65 feet.

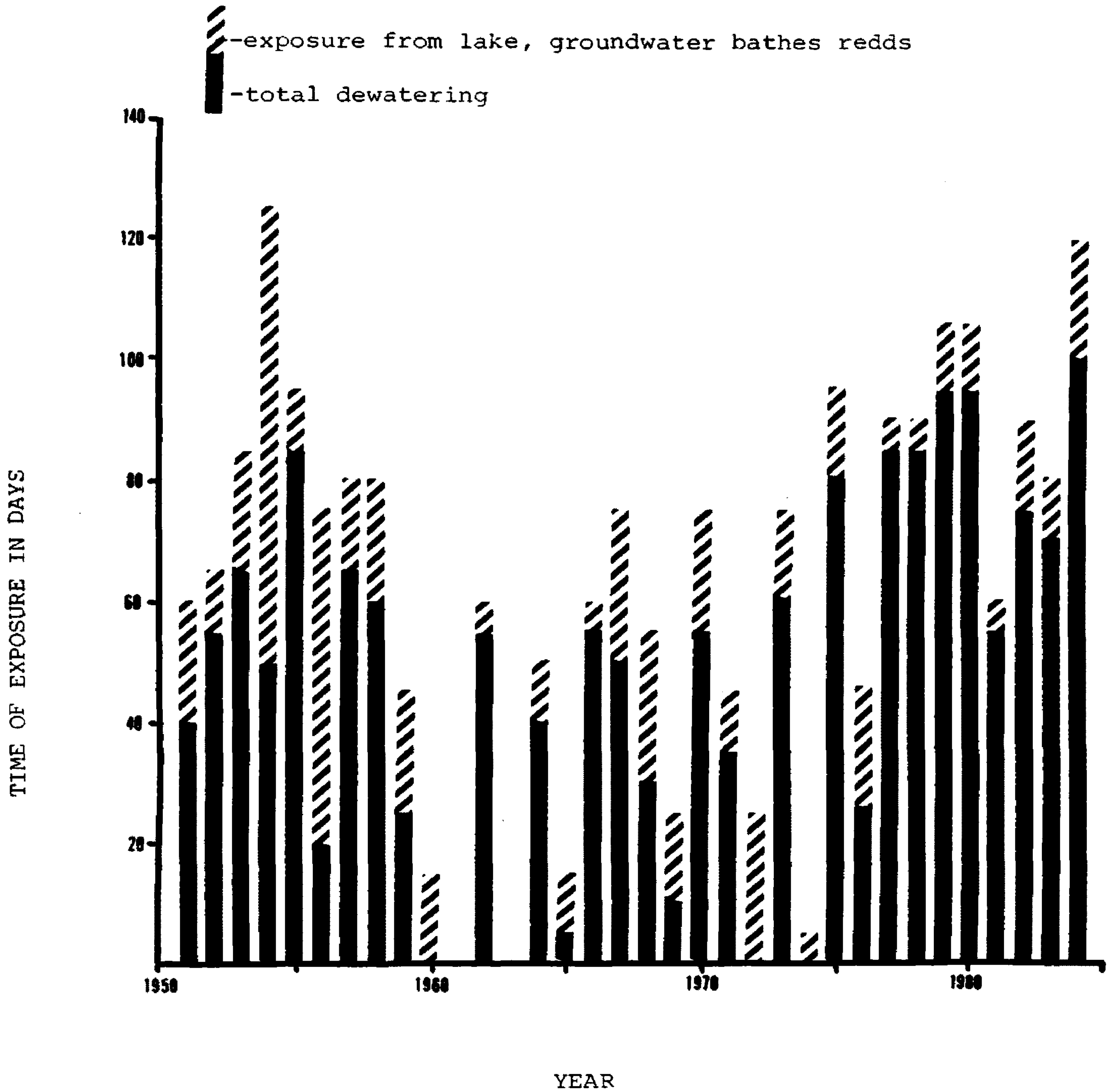


Figure 11: Simulated redd exposure from 1951-1984 at 2886.20 feet.

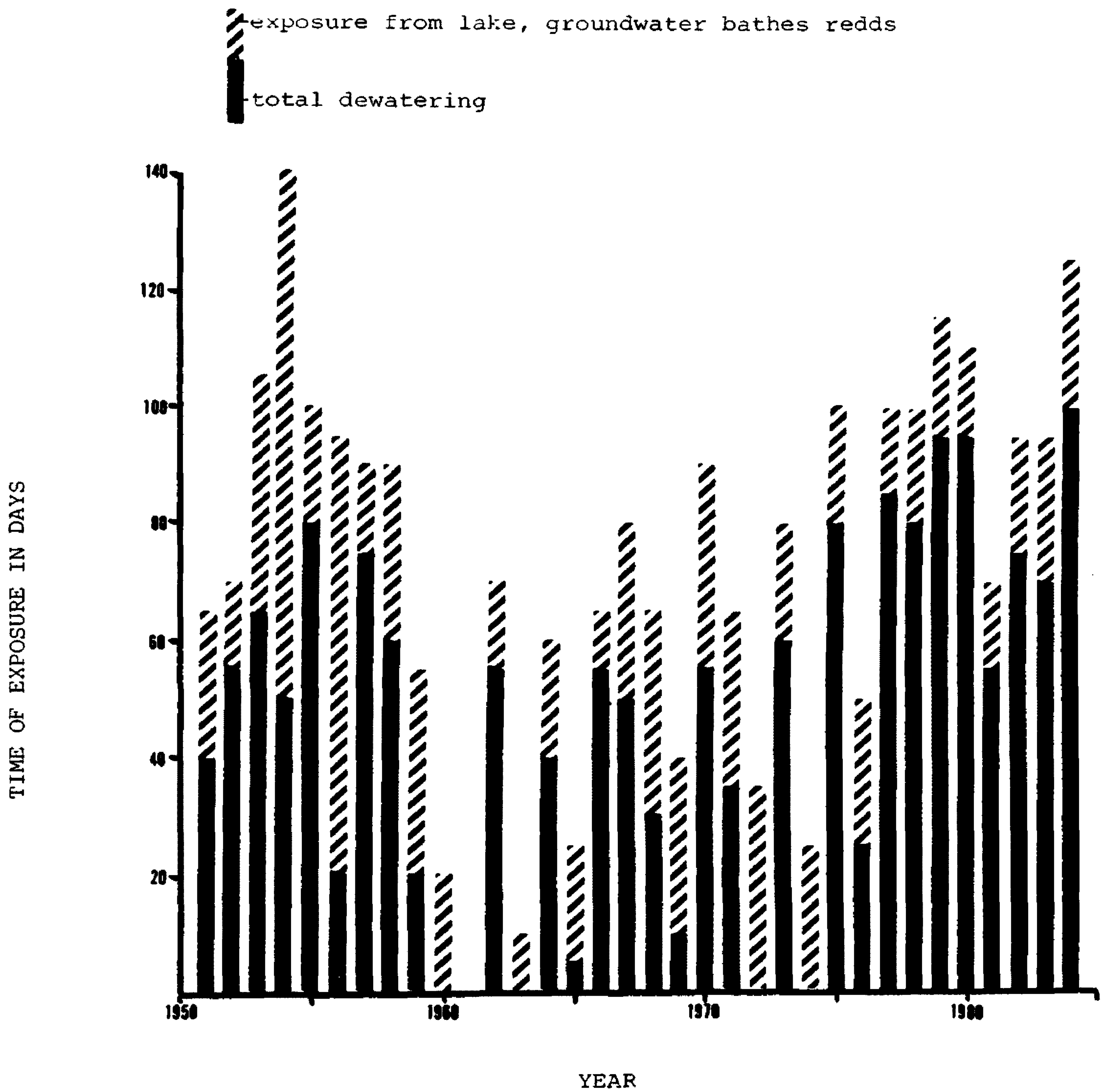


Figure 12: Simulated redd exposure from 1951-1984 at 2886.80 feet.

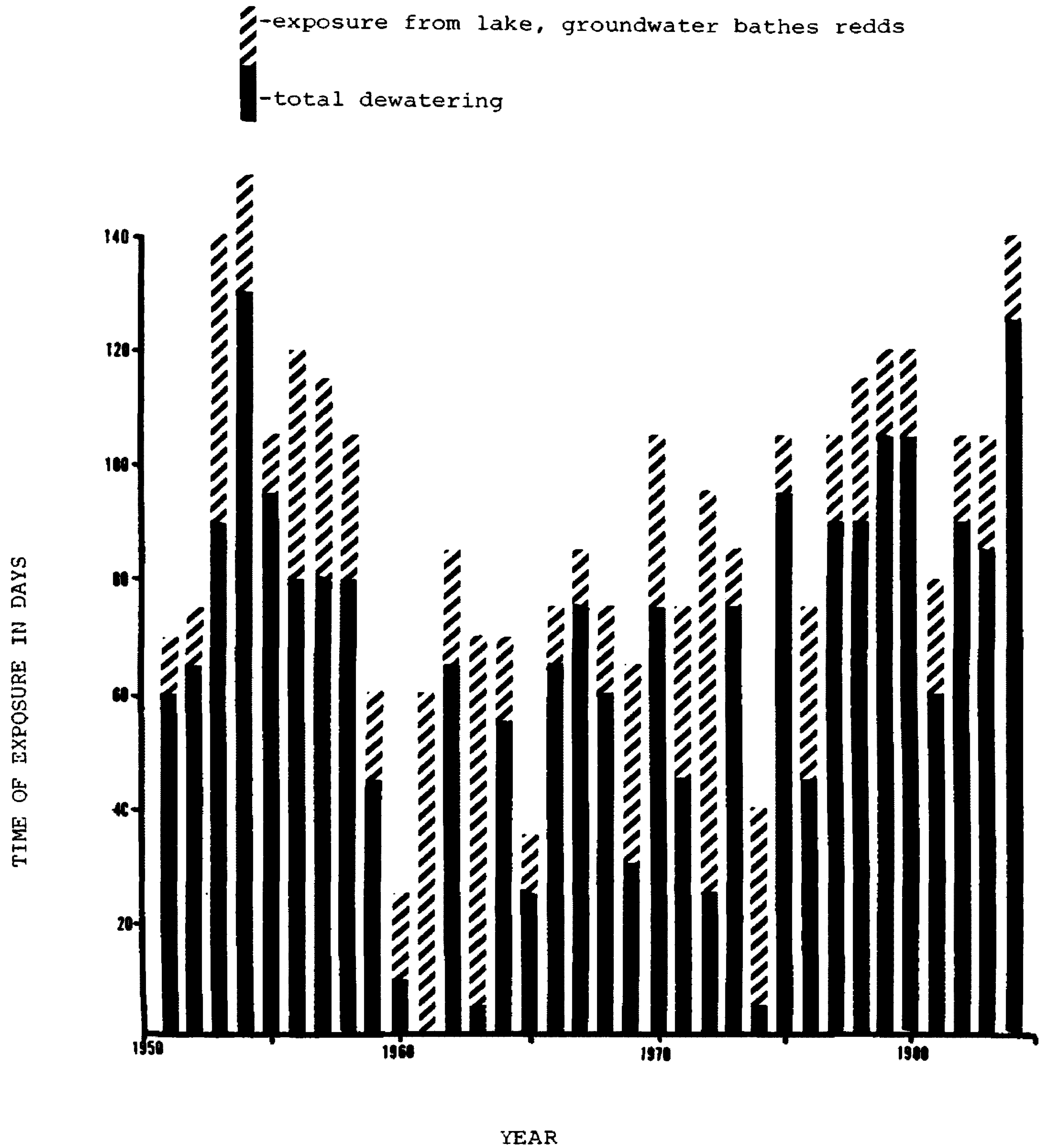


Figure 13: Simulated redd exposure from 1951-1984 at 2887.40 feet.

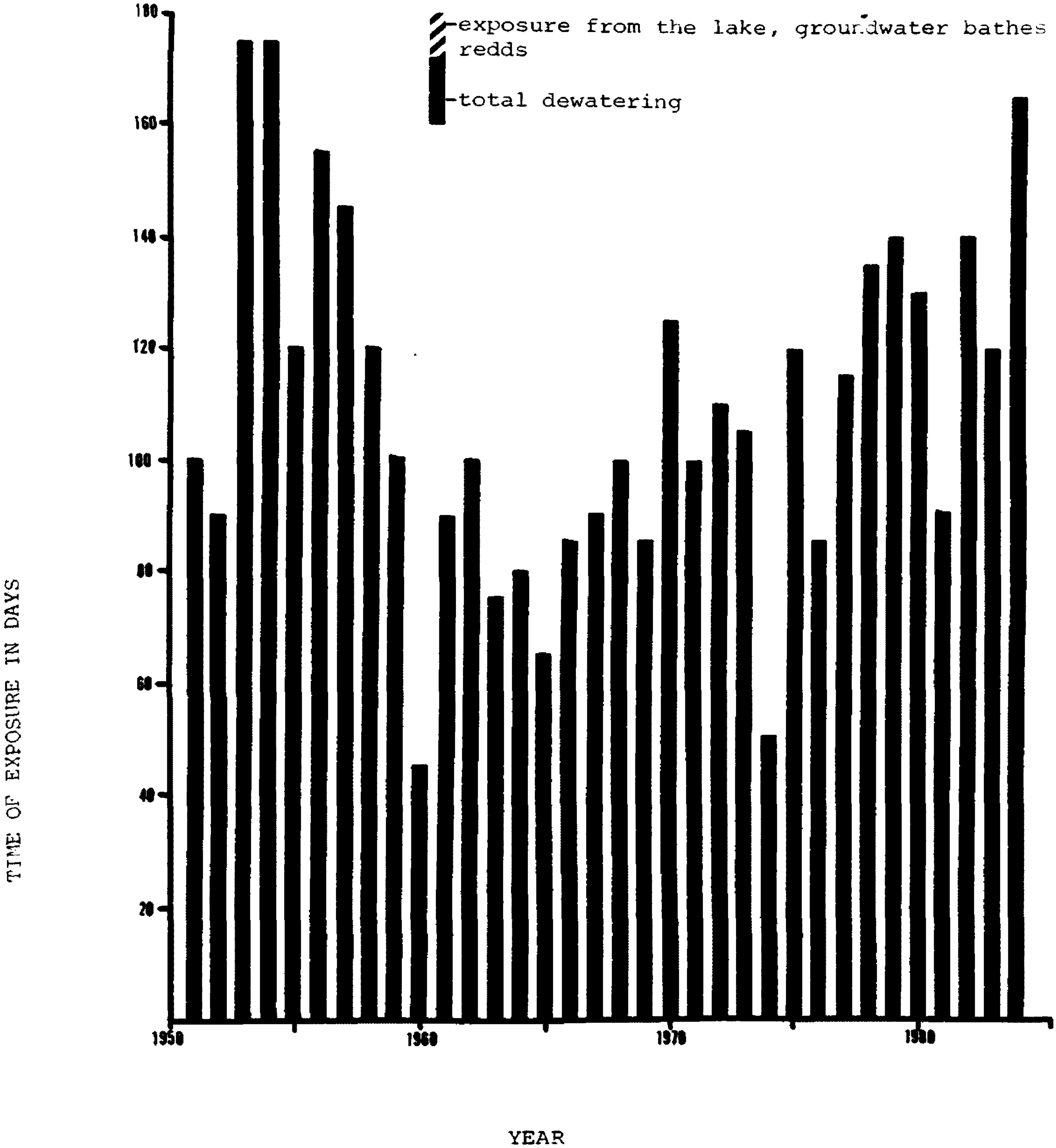


Figure 14: Simulated redd exposure from 1951-1984 at 2888.50 feet.

inches from the surface. This represents the period of total dewatering from both the lake and from groundwater and is represented by the solid portion of each bar. The histograms are thus a means to compare exposure from the lake with exposure from groundwater and hence the mitigating influence of groundwater.

The number of days of exposure are in multiples of five because the time step in the model is five days. One should also bear in mind that the drawdown and therefore the number of days is influenced by the five foot node spacing. For example, the lake elevation may dip below 2884.00 feet but if it doesn't fall more than half the distance between this and the next node, the model won't move the lake boundary and 2884.00 feet will never be exposed in the simulation. Thus the simulated results will underestimate the real exposure time from the lake. The underestimation is greatest at the lower elevations and is a less significant percentage of the total time at higher elevations. The simulated time of exposure is not accurate to the day but can be used to estimate historical averages and to make relative comparisons between years.

Groundwater has increased the amount of time that the redds are wetted and therefore has probably increased the chance of survival (Figures 8-14). The most dramatic increase is at the lowest elevations. Between 2884.00 feet and 2884.75 feet the beach is continually wetted by groundwater. However, at the upper end of the spawning area, groundwater does not keep the redds wetted for any period of time beyond the drawdown of the lake. The exposure times here are identical. One notices that the amount of time that groundwater bathes the redds (represented by the upper part of each bar) is not necessarily constant for a given length of lake drawdown (represented by the entire bar). This is because the lake is not necessarily drawn down at the same rate and it is the rate of drawdown which will affect the length of time that groundwater remains near the surface at a given elevation.

The information from the histograms is summarized further in Table 5. Except for the lower elevations which are constantly wetted by groundwater and the upper elevation which is never wetted, groundwater has wetted the intermediate elevations (with the highest percentage of spawning) redds for an average 30 percent of the time that the lake has exposed them over the past 34 years. The implications of this for the survival of the kokanee eggs could be considerable.

Table 5: Simulated average exposure of the spawning area per year from 1951-1984.

BEACH ELEVATION (FEET)	AVERAGE # DAYS REDDS EXPOSED FROM LAKE	AVERAGE # DAYS REDDS BATHED IN GROUNDWATER	AVERAGE # DAYS OF TOTAL DEWATERING
2884.00	14	14	0
2884.75	32	32	0
2885.65	48	15	33
2886.20	64	16	48
2886.80	74	26	48
2887.40	90	25	65
2888.50	110	0	110

Chapter 5

DISCUSSION

THE MODELED WATER TABLE RESPONSE

The position of the water table at a given node during the lake drawdown is heavily dependent on the relative position of that node on the slope profile of the beach. The slope on the beach is not constant (Figure 4). It is relatively low-angle (5 percent) between 2884.00 feet and 2884.75 feet. The slope steepens to 18 percent to 2885.65 feet then remains at 11 to 12 percent up to 2887.40 feet. In the next five feet, up to 2888.50 feet, the slope steepens again to 22 percent. From the evidence of previous modeling studies (Freeze and Witherspoon, 1967; Munter and Anderson, 1981) one expects a greater probability of groundwater discharge just below a break in slope. The water table tends to reflect the topography of the land surface (Toth, 1962) but where the slope suddenly changes from steep to shallow, groundwater will tend to seep at the base of the steep section. At Skidoo Bay this means that the gravels above the break in slope will tend to be dewatered to a greater depth and the areas of shallow slope will have a higher water table. This is borne out by the results of the modeling. The flat areas closest to the lake have the water table closest to the surface. This is partly due to proximity to the lake but is also a function of the slope profile. In the modeled scenarios these nodes occasionally have head vaues greater than the beach elevation which indicates seepage at the surface. Surface seeps have, in fact, been observed at these elevations at Skidoo Bay.

The nodes which are located immediately above the breaks in slope tend to be quickly dewatered. Part of the reason for this may be that the breaks in slope represent wave-sorted berms on the beach. The berms are made up of well-sorted gravel which probably has a very high hydraulic conductivity. The berms are thus not likely to remain saturated for long. The nodes on the constant part of the slope (2885.65 to 2887.40 feet) are wetted by groundwater an average 30 percent of the time that the lake is down. The variation in percentages of wetted time between the intermediate nodes are due to variations in the rate that the lake is drawn below each node.

The position of the real and modeled water table, on the scale that it affects the redds, is highly dependent on the slope profile of the beach. That raises the question of how constant it has been over the past 34 years. Minor features, such as the wave berms, would not be expected in the same positions, but how much has the overall profile changed? An air photo study of the evolution of the beach since the closure of the dam reveals that the shoreline may not have changed much during the modeling period (Woessner, Brick and Moore, 1985). Kerr dam has kept the present Flathead Lake at a higher average level than the original lake. The higher lake level has resulted in the erosion of the beach and subsequent steepening of the beach profile. In the preceding report, Moore concludes that most of the modifications occurred within the first twenty years following closure of the dam. From 1954 to the present the erosional processes continued, but at a much slower pace as the shoreline began to approach a new equilibrium.

Because the beach profile is significant, the model of Skidoo Bay is very site specific. Generalizations could be inferred from these results about other sites on the lake but any differences in hydraulic conductivity or beach geometry would have to be considered in the comparison.

IMPLICATIONS FOR KOKANEE

An estimate of the rate of egg survival based on the length of exposure from water is necessary to determine the real impact of drawdown on the spawning redds. The Department of Fish, Wildlife and Parks conducted a limited study in an effort to determine this. Live kokanee eggs were planted in artificially constructed redds and the dewatered period was measured (Decker-Hess and Clancey, 1984). "Dewatering" was defined as the length of time of exposure from the lake and did not take groundwater into account. The actual moisture content of the sediment was not measured. During the dewatered interval, the numbers of live and dead eggs were counted and this survival rate was attributed to the length of time that the eggs were exposed. Results of these studies are available for two field seasons, 1982-83 and 1983-84. Since the study did not consider the moisture content of the sediments or the ambient temperature, and since the redds were not sampled daily, it seems most reasonable to consider the results of the 1983-84 season which show the lowest survival rate (Table 6). These survival rates are clearly estimates, not fact.

Table 6: Suvival rates at Skidoo Bay, 1983-84 (from Decker-Hess and Clancey, 1984).

NUMBER OF DAYS DEWATERED	PERCENT CHANCE OF SURVIVAL
**************	**************
0 - 20	50 - 95%
25 - 45	15 - 50%
50 - 85	0 - 15%
more than 85	0%

As the results of the modeling indicate, kokanee are more likely to survive if they spawn at lower elevations. Unfortunately, Fish, Wildlife and Parks data (Decker-Hess and Clancey, 1984) for 1983-84 spawning at Skidoo Bay indicate that only 4 to 5 percent of the redds were located below 2885.00 feet primarily because the substrate was not as suitable. The high water table at the lower elevations doesn't help much. Only 7 percent of the redds were located above 2880.00 feet and were therefore destined for total mortality. The majority of the spawners deposited their eggs between 2886.00 and 2888.00 feet. Figure 15 outlines the extent of the spawning area over the beach in the past three years. The area of highest intersection between these three years falls between 2886.00 feet and 2887.00 feet. This is just below the sharp increase in slope from 2887.00 to 2888.00 feet. During the spawning season, the highest discharge most likely occurs

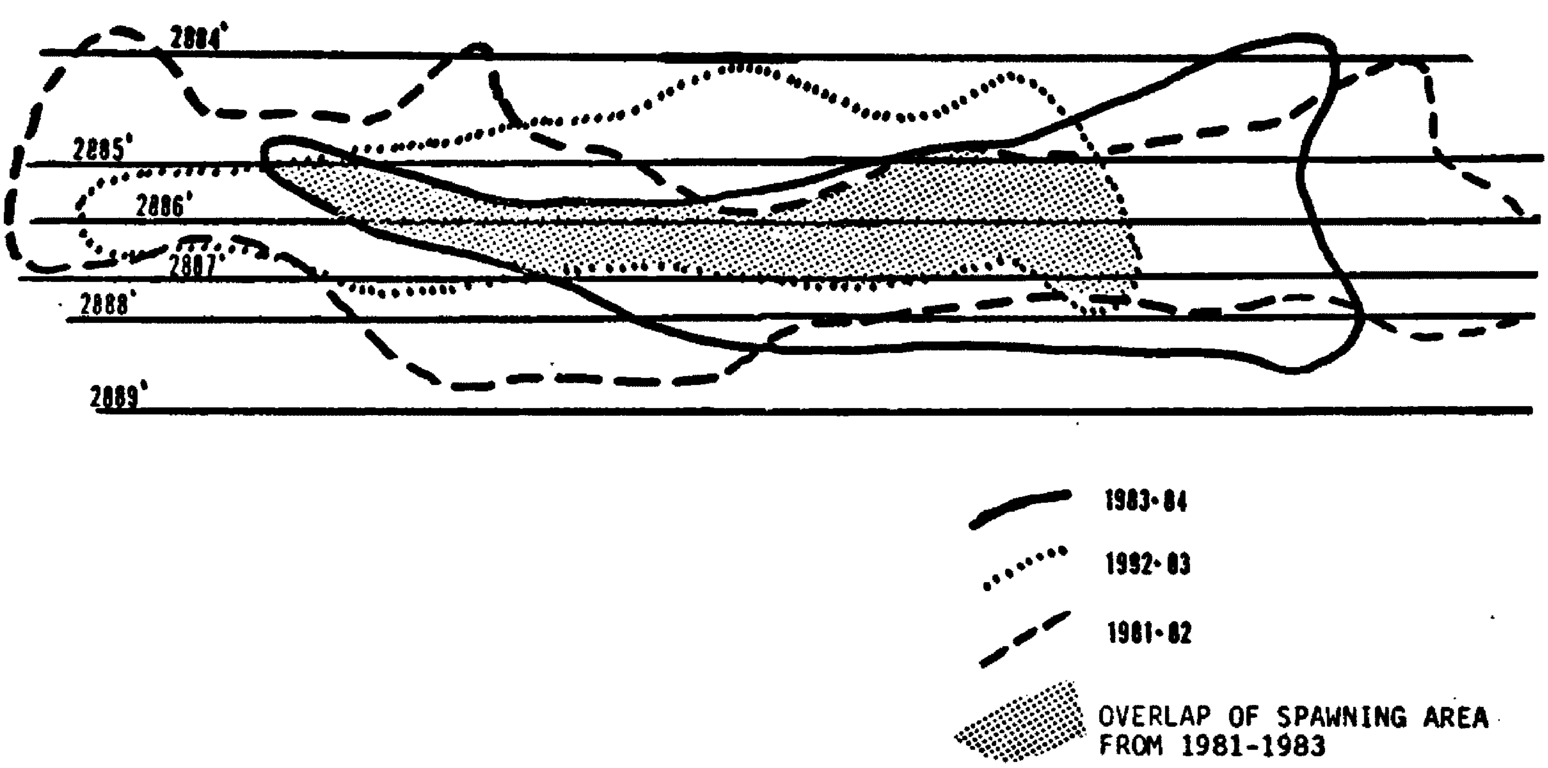


Figure 15: Plan view of the spawning area at Skidoo Bay with elevation contours.

just below this break in slope and probably attracts the spawning fish. Although there is another break in slope at about 2885.00 feet, groundwater discharge tends to decrease exponentially with the distance away from shore (McBride and Pfannkuch, 1975; Lee, 1977; Fellows and Brezonik, 1980; Munter and Anderson; 1981) so the discharge is probably much greater at the higher break. In terms of survival, this means that the majority of the eggs at Skidoo Bay would be covered by groundwater about thirty percent of the time that the lake was down.

To this point, I have discussed averages of the past 34 years but the variations between years may be more important to the fish population. Figures 8 through 14 are useful in comparing the exposure times and chances of survival between years. Two periods of high exposure and mortality are obvious. One is from 1953 to 1958 and the other period started in 1977 and continues through 1984. Since kokanee have a four year life cycle, four sequential years of high mortality could eliminate a shoreline spawning population. The exposure data suggest that this could have happened in both of the periods mentioned above.

It is tempting to try to correlate the length of time of exposure from groundwater with an estimate of the kokanee population over the past 34 years. Unfortunately, the only population data available are not specific enough for this analysis an a number of other factors make it impossible. Fish, Wildlife and Parks personnel use average length data as an estimate of population but there are too many outside variables which make this statistic irrelevent as a basis for comparison with shoreline spawning success. For example, in the 1960's several hatcheries planted up to 2 million kokanee fry in the lake (Decker-Hess and Clancey, 1984). The major problem with the length data though is that it is an estimate for the entire lake population which includes river spawners as well as lake spawners. The lake spawners have made up an increasingly smaller portion of the total population since the 1950's. Will Beattie, a fisheries biologist with Fish, Wildlife and Parks, estimates that 25 to 50 percent of the population spawned on the lakeshore in the 1950's and the rest went to the rivers. By the 1970's, Beattie thinks that 10 percent is an optimistic estimate of lakeshore spawners. Currently, only 2 or 3 percent of the population spawn on the lakeshore. These estimates preclude any sort of quantitative comparison between exposure time and total population but in themselves are evidence that Kerr dam has probably decimated the shoreline spawning population.

CONCLUSIONS

Groundwater undoubtedly mitigates the effects of drawdown of the lake on incubating salmon eggs. The strength of its role is dependent on the hydraulic conductivity and the slope profile of the spawning area and on the presence of surface streams. The sites with streams have a high water table during the winter and enjoy the highest egg survival rates. The sites with a high hydraulic conductivity, and subsequently the lowest water table, have the smallest chance of survival. The sites with low hydraulic conductivity but no stream, such as the Skidoo site, have a water table which drops with lake drawdown but at a slower rate, thus wetting the spawning redds approximately 30 percent of the time that the lake is down.

The modeled results are particularly dependent on the slope profile. Groundwater follows topography except at a break in slope where groundwater tends to seep below the steep section. These discharge areas probably attract the spawning fish while they are submerged, and later keep the redds wetted while they are exposed, as long as the redds are built below the slope change.

Although groundwater has the potential to mitigate the effects of lake drawdown in some cases, it can't compensate in the case where the lake is drawn down rapidly and kept at a low stage for an extended period of time. Model simulation of the rapid drawdowns of 1953 to 1958 and from 1977 to the present supports this statement. It is possible that a carefully planned drawdown schedule could increase the chances of survival in the shoreline redds. If the lake could be drawn down gradually over the elevations where most of the fish have spawned, and not kept as long a time at low stage, the eggs would stand a greater chance of being wetted by groundwater and thus a greater chance of survival.

A definitive statement of kokanee egg survival as related to lake drawdown cannot be made without better data on the length of time that the eggs survive total dewatering. If the Department of Fish, Wildlife and Parks could gather survival data which takes moisture content and temperature into account, it is possible that a comprehensive model could be developed which would combine the biological and hydrogeological influences on kokanee egg survival during lake drawdown.

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Appendix A: Subroutine added to the Prickett-Lonnquist model

```
      MOVE LAKE BOUNDARY
IF (ISTEP.EQ.1) KT=2
IF (ISTEP.EQ.1) A(KT)=((H(20,1)-H(19,1))/2.0)+H(19,1)
WRITE(OUT,622)A(KT)
22        FORMAT(F10.2)
IS=ISTEP
WRITE(OUT,622)FL(IS)
IF(KT.EQ.2) GO TO 628
IF (FL(IS).GT.A(KT-1)) GO TO 625
28        IF (FL(IS).GT.A(KT)) GO TO 630
I1=22-KT
DO 621 J=1,4
SF2(I1,J)=.1
21        CONTINUE
I2=21-KT
I3=20-KT
KT=KT+1
WRITE(OUT,624) KT
24        FORMAT(I3)
A(KT)=((H(I2,1)-H(I3,1))/2.0)+H(I3,1)
GO TO 630
25        IF(FL(IS).GT.A(KT-1)) KT=KT-1
IF(KT.EQ.2) GO TO 629
IF(FL(IS).GT.A(KT-1)) GO TO 625
29        II2=22-KT
DO 626 J=1,4
SF2(II2,J)=1E+31
H(II2,J)=HU(II2)
26        CONTINUE
WRITE(OUT,624) KT
          DELTA=DELTA
  630     CONTINUE
```

The subroutine is inserted into the model so that it is called after the first time step, before the head calculations of the second and subsequent time steps.

APPENDIX B: Model Results: Tabulation of the number of days of exposure from the lake (L) and the water table (WT) at the nodal elevations on the spawning area.

YEAR	2884.00		2884.75		2885.65		2886.20		2886.80		2887.40		2888.50	
	L	GW	L	GW	L	GW	L	GW	L	GW	L	GW	L	GW
1951	10	0	30	0	40	30	60	40	65	40	70	60	100	100
52	30	0	30	0	55	50	65	55	70	55	75	65	90	90
53	30	0	50	0	65	50	85	65	105	65	140	90	175	175
54	20	0	35	0	50	35	125	50	140	50	150	130	175	175
55	25	0	60	0	80	60	95	75	100	80	105	95	120	120
56	0	0	0	0	20	0	75	20	95	20	120	80	155	155
57	50	0	65	0	75	65	80	65	90	75	115	80	145	145
58	30	0	50	0	60	50	80	60	90	60	105	80	120	120
59	0	0	10	0	20	10	45	25	55	20	60	45	100	100
60	0	0	0	0	0	0	15	0	20	0	25	10	45	45
61	0	0	0	0	0	0	0	0	0	0	60	0	90	90
62	15	0	40	0	55	40	60	55	70	55	85	65	100	100
63	0	0	0	0	0	0	0	0	10	0	70	5	75	75
64	0	0	35	0	40	30	50	40	60	40	70	55	80	80
65	0	0	0	0	5	0	15	5	25	5	35	25	65	65
66	10	0	30	0	55	30	60	55	65	55	75	65	85	85
67	0	0	15	0	50	15	75	50	80	50	85	75	90	90
68	0	0	15	0	30	15	55	30	65	30	75	60	100	100
69	0	0	0	0	10	0	25	10	40	10	65	30	85	85
70	0	0	45	0	55	45	75	55	90	55	105	75	125	125
71	0	0	25	0	35	25	45	35	65	35	75	45	100	100
72	0	0	0	0	0	0	25	0	35	0	95	25	110	110
73	30	0	55	0	60	55	75	60	80	60	85	75	105	105
74	0	0	0	0	0	0	5	0	25	0	40	5	50	50
75	50	0	65	0	80	65	95	80	100	80	105	95	120	120
76	0	0	0	0	25	0	45	25	50	25	75	45	85	85
77	25	0	60	0	90	60	90	85	100	85	105	90	115	115
78	25	0	45	0	80	45	90	85	100	80	115	90	135	135
79	55	0	85	0	95	85	105	95	115	95	120	105	140	140
80	65	0	80	0	95	80	105	95	110	95	120	105	130	130
81	0	0	15	0	55	15	60	55	70	55	80	60	90	90
82	0	0	55	0	75	55	90	75	95	75	105	90	140	140
83	0	0	35	0	70	35	80	70	95	70	105	80	120	120
84	20	0	45	0	100	65	120	100	125	100	140	125	165	165