MADISON RIVER
THERMAL SIMULATION STUDY

by

Richard Vincent
Montana Department of Fish, Wildlife and Parks
Bozeman, Montana

in Cooperation with

Jim Dooley and Jim Horn
Water and Power Resources Service

February 11, 1981

Funding or Services Provided by

Water and Power Resources Service
Bureau of Land Management
Gallatin-Madison Chapter of Trout Unlimited
Montana Department of Fish, Wildlife and Parks
Blue Ribbons of Big Sky Country-
Area-wide Planning Organization
Montana Power Company

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BACKGROUND

The Madison River, a nationally famous "blue ribbon" trout stream is formed in the northwestern portion of Yellowstone National Park with the confluence of the Gibbon and Firehole Rivers. It flows in a northerly direction for about 140 miles where it joins the Jefferson and Gallatin Rivers to form the Missouri River at Three Forks (Figure 1). There are two man-made impoundments built on the Madison River: (1) Hebgen which is located about 1.5 miles west of the YNP boundary, and (2) Ennis which is located about seven miles north of the Town of Ennis.

Hebgen Dam which was built in 1915 is being used for water storage and flow regulation for downstream power generation at Ennis Dam and other sites further downstream. Ennis or Madison Dam was constructed in 1900 to provide electrical power for southwestern Montana. The reservoir formed by this dam fluctuates little since it is used primarily to establish head for the water turbines.

Ennis Reservoir is located in a shallow basin immediately upstream from Bear Trap Canyon and over the last 75-80 years has slowly became more shallow due to sediment deposition from upstream sources (Figure 2). The wide shallow nature of Ennis Reservoir has created a "heat trap" which warms the lower Madison River beyond what it would be if no reservoir existed. In 1977, U.S.G.S., using thermal imagery on aerial flights, confirmed that solar radiation was the primary factor causing the thermal problem in and below Ennis Reservoir (Boettcher, Dooley and Horn, 1979). This warming is extensive enough to cause a serious degradation of 35 miles of this "blue ribbon" trout fishery. Under the right set of climatic conditions (above average summer temperatures and/or unusually low water) or increased sediment deposits in the reservoir, this situation could become critical. Vincent (1978) found that given similar air temperatures, the lower Madison River was 1-2°F warmer in the mid 1970's than the early 1960's which probably was due to increased sediment depths in the reservoir. There have been periodic fish kills in this reach of the Madison during the last thirty years which may have been due to this thermal problem.

In 1961, (Heaton) found that Ennis Reservoir warmed the Madison River 10-15°F during the summer months from what it was above the reservoir. Vincent (1978 and 1979) substantiated this warming, plus found that this degree of warming substantially decreased growth rates of older brown and rainbow trout from growth rates found above Ennis Reservoir. Fishermen catch rates were also severely reduced during the summer period because of this decreased feeding activity. The average June-August water temperatures above Ennis Reservoir near Varney bridge were 59.2°F versus 66.4°F below Ennis Reservoir near Norris bridge for 1977 and 58.3°F versus 64.5 F in 1978. High water temperatures have been shown by other investigators to decrease salmonid growth rates. Brett, et.al. (1967) showed that as water temperatures increased past 59°F, growth rates slowed until 73°F was reached when growth ceased. They also found young sockeye salmon grew best at 59°F with growth slowing at the higher water temperatures.

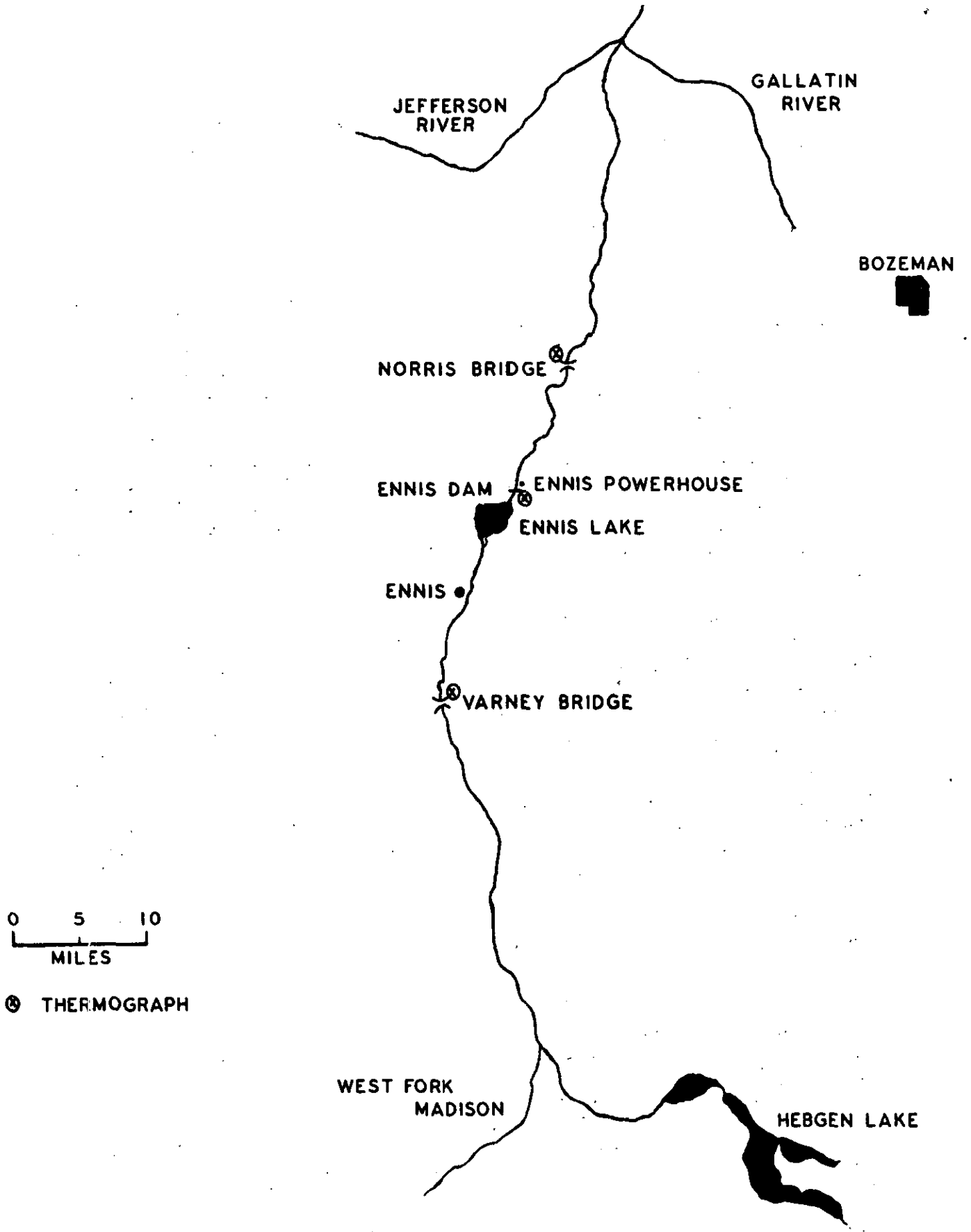

FIGURE 1. Map of Madison River

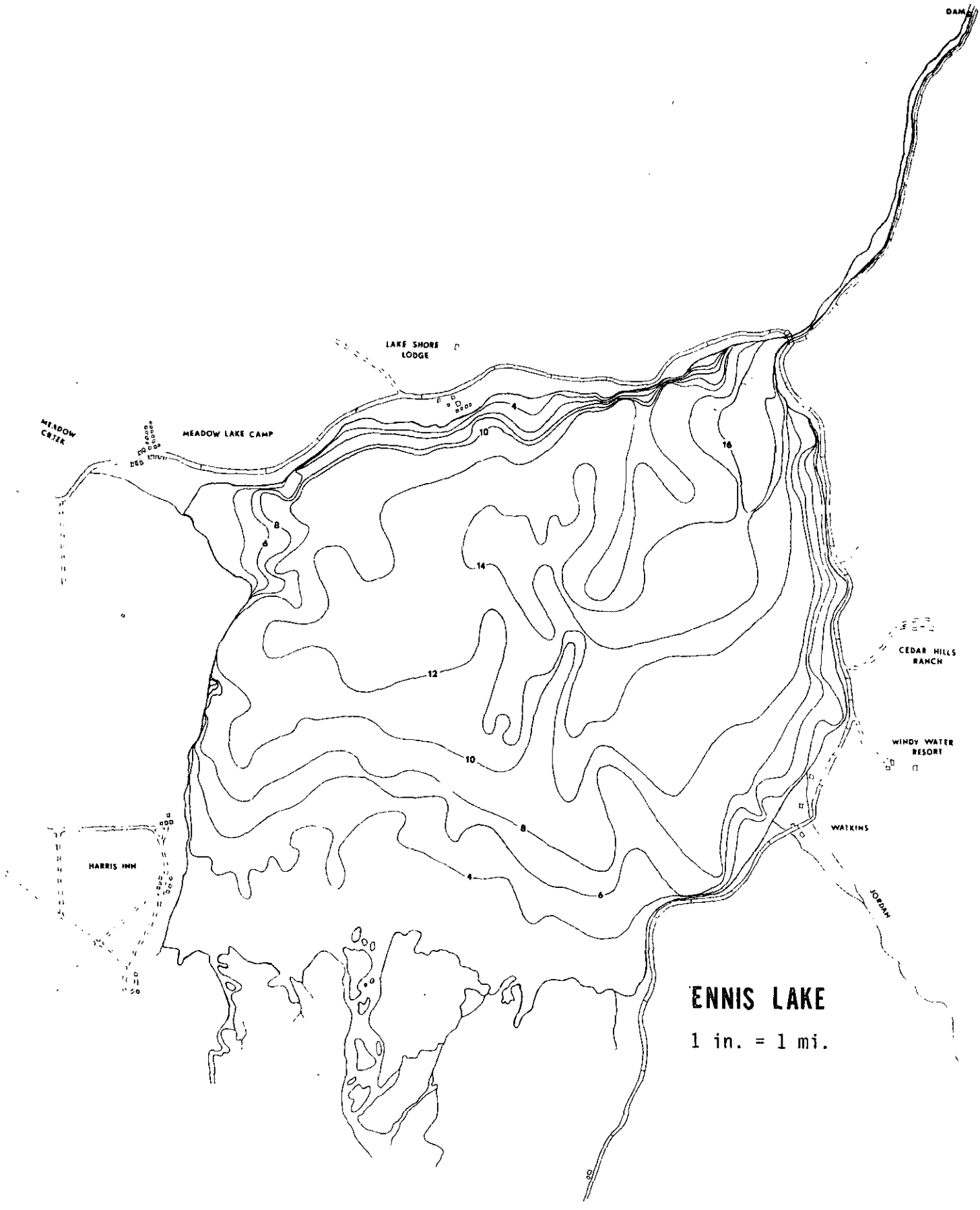

FIGURE 2. Depth contour map of Ennis Reservoir.

If the thermal problem could be solved, considerable recreational trout fishing could be provided during the summer months involving opportunities on the Missouri River as well as the Lower Madison River.

OBJECTIVES

The purpose of this study was to determine through computer models what water temperatures would result in the Madison River below Ennis Reservoir under various options proposed to correct the thermal problem. These simulated temperatures for both 1973 and 1977 were compared to conditions presently existing in the lower Madison River. Five options were designated to be examined to determine their relative success in cooling the lower Madison River during the summer months when water temperatures damage the trout fishery and approach the critical levels.

Option I - LOWERING EXISTING RESERVOIR LEVEL

This option was considered because of two promising factors: (1) the lowering of the reservoir would reduce the surface area of the reservoir allowing less solar heat absorption, and (2) the flow-through time would be reduced as total volume is reduced, possibly allowing less time for solar heating of the water (Table 1).

Table 1. Surface acreage and reservoir volume remaining after various levels of level draw-down versus flow-through time using 1200 cfs in and out flow.

Draw Down (ft.)	Surface Acres[1/] Remaining	Volume Remaining (Acre-Ft.)	Flow-Through Time (days)
0	3781	34,675	14.6
4	3151	20,811	8.7
6	2780	14,880	6.3
8	2461	9,639	4.1
10	1990	5,188	2.2
12	1171	2,077	0.9
14	359	497	0.2

[1/] Data from Vincent, 1978, excludes 1000 acre-ft. downstream from county bridge.

Option II - NO ACTION

Allow the reservoir to continue to fill naturally with sediments until the reservoir disappears enough to correct the thermal problem.

Option III - RAISE THE DAM

Raise the reservoir level by raising existing dam until thermocline of sufficient size to allow withdrawal of cool bottom water.

Option IV - REDUCE RESERVOIR SURFACE AREA

Reduce the existing surface area of the reservoir without lowering or raising the surface elevation. This option represents what would happen if the entire surface area of the reservoir was reduced either 70 or 80 percent. It would take some form of diking to accomplish this option. The surface acreage would be reduced from the present 3791 acres to 1134 acres under the 70% reduction or 756 acres at the 80% reduction (Figure 3).

Option V - COMPLETE CHANNELING OR DAM REMOVAL

Removal of existing dam and reservoir or the channeling around either the east or west shorelines to the present county bridge near the north end of the reservoir. This option basically returns the Madison River to its original state where minimal heating would occur.

Option VI - REDUCE RESERVOIR'S SHALLOW AREA

Reduce the existing surface area of the reservoir without lowering or raising the surface elevation (Figure4). This could be accomplished through construction of large dikes on the west and east shore beginning at the south end of the reservoir. This dike could be constructed either on or near the 10 or 12 foot depth contour line with space allowing passage of inflowing water from the Madison River. This would reduce the surface area of the shallow portion of the reservoir, plus reduce the flow-through time (Table 2).

Table 2. Comparison of flow-through time and active surface acreage with dikes separating the shallow areas from deeper lake areas. Inflow and outflows assumed to be 1200 cfs.

Percent Reduction of Surface Area	Remaining Surface Acres	Flow-Through Time (days)
0	3791	14.6
0 to 10 ft. - 70%	2527	5.9
0 to 10 ft. - 80%	2328	4.7
0 to 12 ft. - 70%	1954	5.0
0 to 12 ft. - 80%	1693	3.6

PROCEDURES

This report is a summation of work done by the U.S.G.S. in 1977 using thermal imagery (Boettcher, Dooley and Horn, 1979) and the mathematical computations made by Dooley and Horn (1980). Two temperature models were used to simulate the changes in water temperatures under various selected options to change the river-reservoir system. They were a lake simulation model - Corps of Engineers/WRE Temperature Model and a river temperature and travel time simulation model-Green.

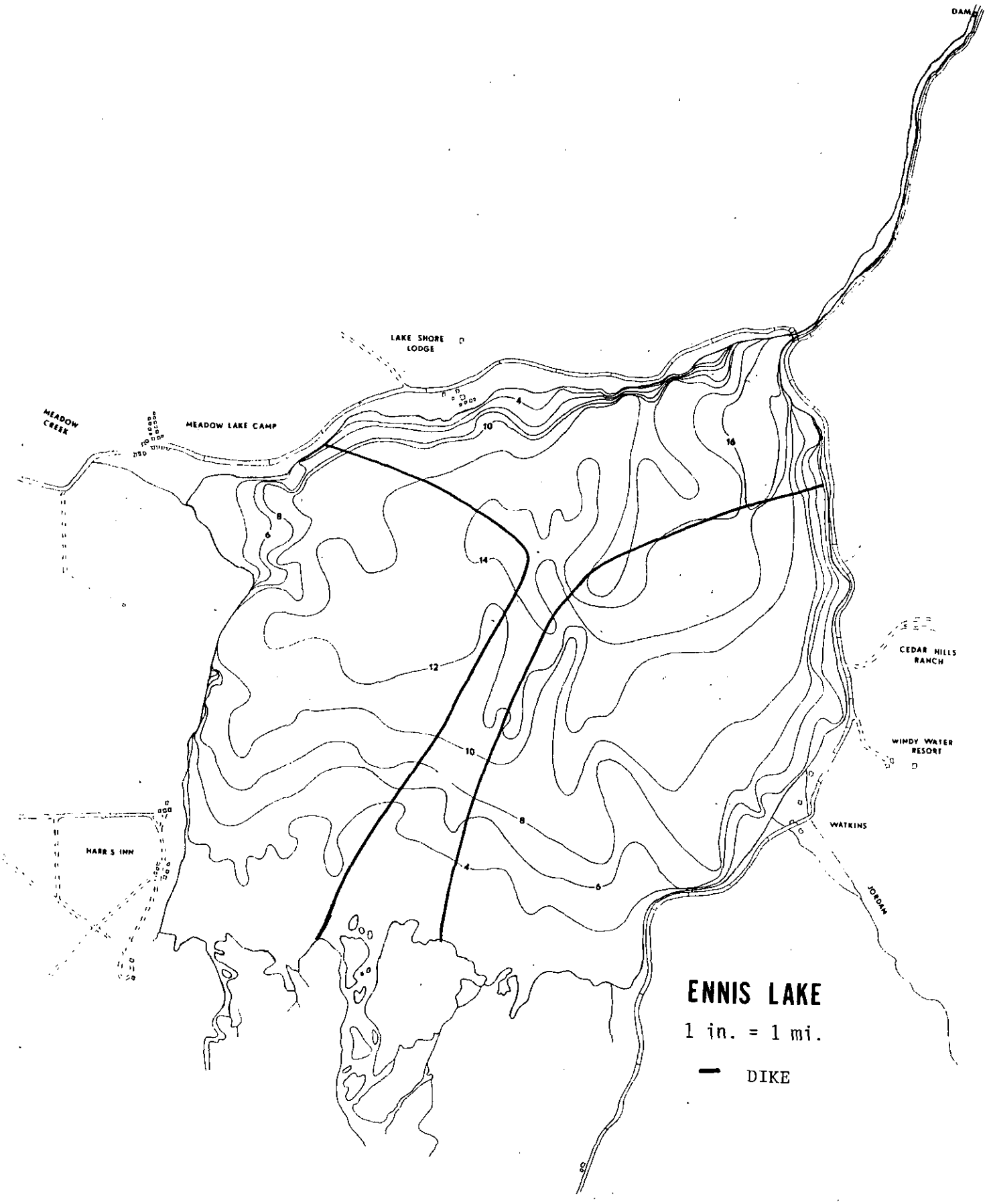

FIGURE 3. Depth contour map of Ennis Reservoir shows potential diking.

Reservoir surface areas, volumes and flow-through times were computed from a depth contour map made by the Montana Dept. of Fish, Wildlife and Parks in August, 1977. The number of days over 70°F and 80°F plus maximum expected temperatures were calculated by multiplying the daily average temperature by a constant 1.1. This constant was obtained by using existing temperature data from June through August period for the Varney and Norris thermographs and determining the relationship between maximum and average temperatures. There are existing water temperature recording sites at Varney bridge, Ennis Powerhouse and Norris bridge since 1972.

RESULTS

Option I - LOWERING EXISTING RESERVOIR LEVEL

Simulated temperatures were computed as the level was lowered by two foot intervals. The simulated temperature calculated for the Madison River below Ennis Reservoir shows little change in the monthly average water temperatures with depth changes up to 12 feet (Table 3). Using the critical summer months of June, July and August for the 1973 climatic conditions, there was only a 1.9°F drop in the average temperature and a 3°F reduction in the maximum expected temperature (Table 4). There was a 9% reduction in the number of days the water temperature exceeded 70°F and an elimination of any days exceeding 80°F.

Option II - NO ACTION

In determining what would happen if the reservoir was left alone to fill naturally with sediments, simulated water temperatures were derived upon filling the reservoir with 3, 6 and 9 feet of sediments. As more sediments were added, the average June-August temperature remained about the same using both 1973 and 1977 climatic data (Table 5). But the maximum expected temperature increased with each addition of sediments as well as the days over 80°F (Table 6). This is similar to what was found by Vincent (1978), that the Madison River below Ennis Reservoir was warmer in the 1970-75 period given the same air temperature as found in the 1960-66 period. This 1977 data basically suggested that during the hot period the Madison River was warmer and during the cool periods it was cooler, which should keep the average temperatures similar. This change in the temperature from the 1960's to the 1970's was speculated to be from additional sediments being deposited in Ennis Reservoir.

Option III - RAISE THE DAM

Simulated water temperatures computed after raising the reservoir level from 10-40 feet show a steady decrease in the June-August temperatures with each 10 foot raise in the reservoir level (Table 7). Using 1973 climatic conditions, the average July temperature decreased 8.7°F and August 3.0°F. Similar decreases were shown using 1977 data. The maximum daily temperature decline from 81°F in 1973 under existing reservoir levels to a 76°F maximum with a 40 foot height increase (Table 8). There was a 8°F drop in the maximum temperature with a 40 foot increase using 1977 data. There was a 44% drop in the number of days exceeding 70°F in 1973 and 1977, plus an elimination of days over 80°F.

Option IV - REDUCE RESERVOIR SURFACE AREA

When the reservoir's surface area was reduced to include only 20-30% of the original surface area, the average temperature decreased for all months from May through September with the warmest months (July and August) showing the greatest decline, 5 to 5.7°F (Table 9). The 80 percent reduction had the greatest effect; as temperatures over 80°F being eliminated, the days over 70°F being reduced 27% and the maximum temperature being lowered from 81°F to 73°F (Table 10).

Option V - COMPLETE CHANNELING OR DAM REMOVAL

Simulated water temperatures resulting from either removal of Ennis Dam or canaling around the east or west shoreline shows a significant decrease in the average monthly temperatures during the months of May through September from existing conditions using 1973 and 1977 climatic conditions (Table 11). The decrease in average monthly temperatures ranged from 4.9°F in September to 10.4°F in July for 1973 climatic conditions and using 1977 climatic conditions, there was a 6.6°F drop for July and 4.9°F for August. Using both 1973 and 1977 data, the days over 70°F were eliminated in 1973 and a 57% reduction in 1977 (Table 13). There was an elimination of days where the water temperature exceeded 80°F with the maximum temperature found decreasing from 81°F to 68°F in 1973 and decreasing from 82°F in 1977 to 74°F. Using 1973 data, the Norris station actually was cooler than the Madison River at the Varney station.

Option VI - REDUCE RESERVOIR'S SHALLOW AREA

When the reservoir's surface area was reduced to include only 20 to 30% of the original area between 0-10 feet or 0-12 feet, the average temperature decreased for all months from May through September. The warmest months (July and August) showed only 2.9 to 3.0°F drop in average temperature (Table 12). The reducing of the 0-12 foot surface area 80% had the greatest effect with temperatures over 80°F being eliminated with little reduction in the number of days over 70°F and the maximum temperature lowered from 81°F to 76°F (Table 14).

SUMMARY

The effectiveness of the various options chosen to solve the lower Madison River thermal problem were chosen on the basis of how well they returned the water temperature in the lower Madison River to temperatures favorable to good trout growth and survival. Optimum trout growth probably centers around 57-61°F with 59°F being the optimum. Any temperatures past 73°F were considered detrimental with temperatures in the 80's being critical and over 85°F probably lethal.

In comparing the five options presented as to their effect on the lower Madison River's thermal problem, only Option II (NO ACTION) actually caused the river to be warmer than it would be under existing conditions. With up to 9 feet of sediments being added to Ennis Reservoir, monthly average temperatures remained similar to those found with existing sediment levels, but

daily maximum temperature increased and the number of days over 80°F were doubled. Using the 1977 simulation, an average air temperature year, the maximum expected temperature reached 84°F with 6 feet of sediment and 86°F with 9 feet of sediment. These temperatures are approaching the critical lethal points for salmonids. Option I (LOWER RESERVOIR LEVEL), even a 12 foot draw down offers a minimal relief from the high water temperatures as the June-August average water temperature was 63.7°F, similar to temperatures found to reduce salmonid growth. Maximum temperatures were reduced to 78°F from 81°F in 1973. Option VI (REDUCE RESERVOIR'S SHALLOW AREA) shows only minimal relief from the high average temperatures found during the June-August periods with the 62.9°F average temperature found with a dike at the 12 foot contour line, although temperatures over 80°F were eliminated.

Option III (RAISE RESERVOIR LEVEL), Option IV (REDUCE RESERVOIR SURFACE AREA) and Option V (COMPLETE CHANNELING OR DAM REMOVAL) offer the greatest reductions in average temperatures during the critical summer period giving temperatures similar to the 57-61°F optimum for growth of salmonids. Maximum expected temperatures were the lowest for Options IV (REDUCE RESERVOIR SURFACE AREA) and V (COMPLETE CHANNELING OR DAM REMOVAL) with temperatures staying below 74°F.

RECOMMENDATIONS

Additional investigations are needed to evaluate Options III (RAISE RESERVOIR LEVEL), IV (REDUCE RESERVOIR SURFACE AREA) and V (COMPLETE CHANNELING OR DAM REMOVAL) to determine social, economic and environmental impacts to aid in selecting the most viable solution to eliminate the Lower Madison Thermal Problem.

Table 3. Option I - Comparison of projected average monthly water temperatures for the Madison River immediately below Ennis Reservoir at the powerhouse for various elevation levels Ennis Reservoir assuming 1973 and 1977 air temperatures and other climatic viables. Temperatures shown in degrees Fahrenheit.

Reservoir levels (Feet below full capacity - 4,841 above mean sea level)					
Month	0'	-2'	6'	10'	12'
		1973			
May	51.3	51.4	51.1	50.4	50.8
June	57.5	57.4	57.0	56.1	56.5
July	69.5	68.7	68.7	68.4	67.6
August	69.7	69.3	68.5	67.7	67.0
September	56.5	56.2	55.6	55.2	55.0
		1977			
May	50.5	50.5	50.4	1/	1/
June	65.8	65.7	65.2	"	"
July	69.0	68.6	67.8	"	"
August	67.7	67.4	66.6	"	"
September	59.4	59.2	58.8	"	"

1/ Depth interval not found on computer program.

Table 4. Option I - Comparison of projected water temperatures over 70°F and 80°F and expected maximum temperatures for the Madison River below Ennis Reservoir for various reservoir levels beginning with existing level of 4,831 feet above mean sea level. Data projected using 1973 and 1977 climatic conditions. Temperatures shown in degrees Fahrenheit.

	Reservoir Levels (Feet below full capacity)				
	0	-2 ft.	-6 ft.	-10 ft.	-12 ft.
		June-August, 1973			
Days over 70°F	64	61	61	61	58
Days over 80°F	3	2	2	0	0
Maximum Temp.	81°	80°	80°	79°	78°
		June-August, 1977			
Days over 70°F	75	70	69	1/	1/
Days over 80°F	6	6	7	"	"
Maximum Temp.	82°	82°	83°	"	"

1/ No computations made for this level.

Table 5. Option II - Comparison of projected average monthly water temperatures for the Madison River below Ennis Reservoir at the powerhouse with various depths of sediments added to present reservoir bottom. Data projected using 1973 and 1977 climatic conditions. Temperature shown in degrees Fahrenheit.

Month	Depth of Sediment Added to Existing Reservoir Bottom			
	0 Feet	3 Feet	6 Feet	9 Feet
		1973		
May	51.3	49.5	51.7	51.7
June	57.5	57.2	57.2	56.5
July	69.5	69.7	69.8	71.2
August	69.7	69.7	69.6	69.1
September	56.5	56.4	55.9	55.5
		1977		
May	50.5	50.6	50.7	50.3
June	65.8	66.1	66.3	66.0
July	69.0	69.0	68.8	68.3
August	67.7	67.6	67.3	66.5
September	59.4	59.4	59.3	59.3

Table 6. Option II - Comparison of projected water temperatures over 70°F and 80°F and maximum expected temepratures for the Madison River below Ennis Reservoir with additional sediment levels being added to existing reservoir bottom. Data projected using 1973 and 1977 climatic conditions. Temperatures shown in degrees Fahrenheit.

Depth of Sediment Added to Existing Reservoir Bottom

	0 ft.	+3 ft.	+6 ft.	+9 ft.
	June-August, 1973			
Days over 70°F	64	63	62	62
Days over 80°F	3	6	7	7
Maximum Temp.	81°	81°	82°	82°
	June-August, 1977			
Days over 70°F	75	72	71	71
Days over 80°F	6	11	11	13
Maximum Temp.	82°	83°	84°	86°

Table 7. Option III - Comparison of projected average monthly water temperatures for the Madison River below Ennis Reservoir at the powerhouse with present reservoir levels raised at 10 foot intervals. Data projected using 1973 and 1977 climatic conditions. Temperatures shown in degrees Fahrenheit.

Amount of Increase in Reservoir Level From Existing Height (4,841 ft.)

Month	0 Feet	10 Feet	20 Feet	30 Feet	40 Feet
			1973		
May	51.3	50.3	48.2	46.2	43.3
June	57.5	56.4	56.1	53.8	52.0
July	69.5	68.9	66.6	63.1	60.8
August	69.7	70.4	70.4	67.9	66.7
September	56.5	58.3	60.2	61.5	62.0
			1977		
May	50.5	49.1	46.9	45.3	44.4
June	65.8	63.6	60.7	56.7	53.4
July	69.0	68.8	67.7	65.0	62.4
August	67.7	68.4	68.8	67.3	66.1
September	59.4	60.0	60.6	60.4	61.1

Table 8. Option III - Comparison of projected water temperatures over 70°F and 80°F and expected maximum temperatures for the Madison River below Ennis Reservoir for increased reservoir levels above the existing 4,831 foot level. Data projected using 1973 and 1977 climatic conditions. Temperatures shown in degrees Fahrenheit.

	Increase in Reservoir Level				
	0	+10 ft.	+20 ft.	+30 ft.	+40 ft.
		June-August, 1973			
Days over 70°F	64	63	56	49	36
Days over 80°F	3	0	0	0	0
Maximum Temp.	81°	79°	78°	77°	76°
		June-August, 1977			
Days over 70°F	75	72	65	58	41
Days over 80°F	6	0	0	0	0
Maximum Temp.	82°	79°	78°	75°	74°

Table 9. Option IV - Comparison of projected average monthly water temperatures for the Madison River below Ennis Reservoir at the powerhouse with the reservoir surface areas being altered 70 to 80 percent. Data projected using 1973 climatic conditions. Temperatures shown in degrees Fahrenheit.

Month	Existing Reservoir Size (3,781 acres)	70% of the surface area eliminated (1,134 acres)	80% of the surface area between the 0-10 ft. depth is eliminated (756 acres)
		1973	
May	51.3	48.7	47.8
June	57.5	54.5	53.7
July	69.5	65.4	64.2
August	69.7	65.7	64.7
September	56.5	55.1	54.8

Table 10. Option IV - Comparison of projected water temperatures over 70°F and 80°F and maximum expected temperatures for the Madison River below Ennis Reservoir with surface areas being altered 70 to 80 percent. Data projected using 1973 climatic conditions. Temperatures shown in degrees Fahreheit.

	Existing Reservoir Size (3,781 acres)	70% of the Surface area is eliminated (1,134 acres)	80% of the Surface area is eliminated (756 acres)
	June-August, 1973		
Days over 70 F	64	53	47
Days over 80 F	3	0	0
Maximum Temp.	81°	75°	73°

Table 11. Option V - Comparison of projected average monthly water temperatures for the Madison River at the Varney Station (above Ennis Reservoir), the powerhouse and Norris Stations below Ennis Reservoir assuming no reservoir or the river channeled around the edge of the reservoir. Data projected using 1973 climatic conditions. Temperatures shown in degrees Fahrenheit.

Month	Present Powerhouse	Varney Station	Powerhouse Station	Norris Station
		1973		
May	51.3	46.2	44.9	43.8
June	57.5	51.9	51.4	51.1
July	69.5	60.8	59.1	58.0
August	69.7	60.5	58.8	57.9
September	56.5	53.1	51.6	50.5
		1977		
May	50.5	48.1	49.0	47.0
June	65.8	57.1	58.5	58.5
July	69.0	60.5	60.8	62.4
August	67.7	59.9	60.5	62.8
September	59.4	54.8	54.3	53.9

Table 12. Comparison of projected average monthly water temperatures for the Madison River below Ennis Reservoir at the powerhouse with the reservoir surface areas being altered near the 10 and 12 foot depth contour lines. Temperatures shown in degrees Fahrenheit.

Month	Present Condition (3,781 acres)	70% Reduction of Surface Area	80% Reduction of the Surface Area
	Between the 10 foot contour line		
May	51.3	50.5	49.2
June	57.5	55.4	55.2
July	69.5	68.2	66.7
Aug.	69.7	68.4	67.9
Sept.	56.5	54.7	55.5
	Between the 12 foot contour line		
May	51.3	49.4	49.5
June	57.5	56.5	55.4
July	69.5	66.1	66.6
Aug.	69.7	67.4	66.7
Sept.	56.5	55.8	55.5

Table 14. Option VI - Comparison of projected water temperatures over 70°F and 80°F and maximum expected temperatures for the Madison River below Ennis Reservoir with surface areas being altered at the 10 or 12 foot depth contour line. Data projected using 1973 climatic conditions. Temperatures shown in degrees Fahrenheit.

	Existing Condition (3,781 acres)	70% Reduction of Surface Area		80% Reduction of Surface Area	
		0-10 ft. (2,527 acres)	0-12 ft. (1,954 acres)	0-10 ft. (2,348 acres)	0-12 ft. (1,693 acres)
		June-August, 1973			
Days over 70°F	64	61	57	61	56
Days over 80°F	3	0	0	0	0
Maximum Temp.	81°F	78°F	76°F	77°F	76°F

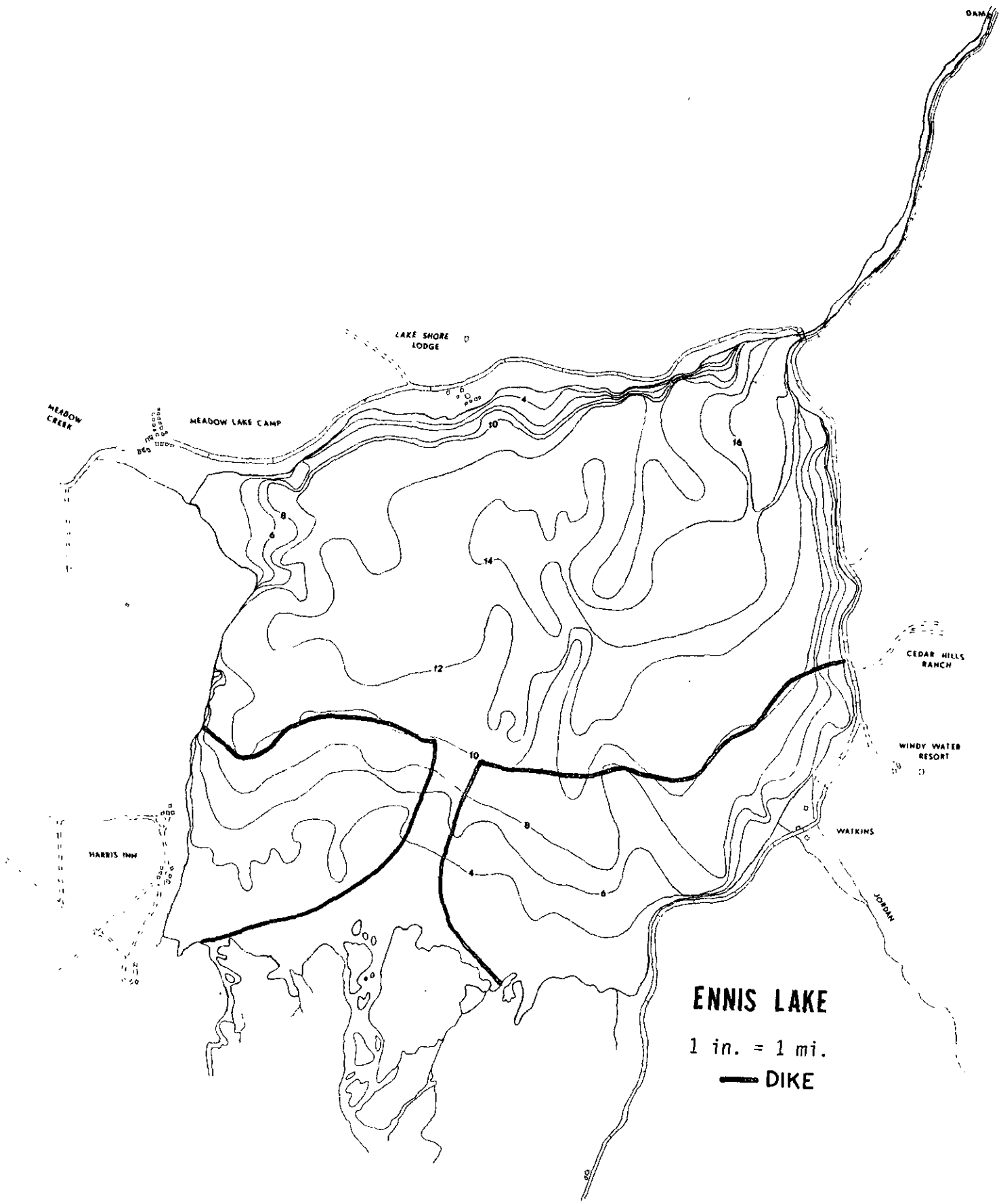

FIGURE 4. Depth contour map of Ennis Reservoir shows potential diking.

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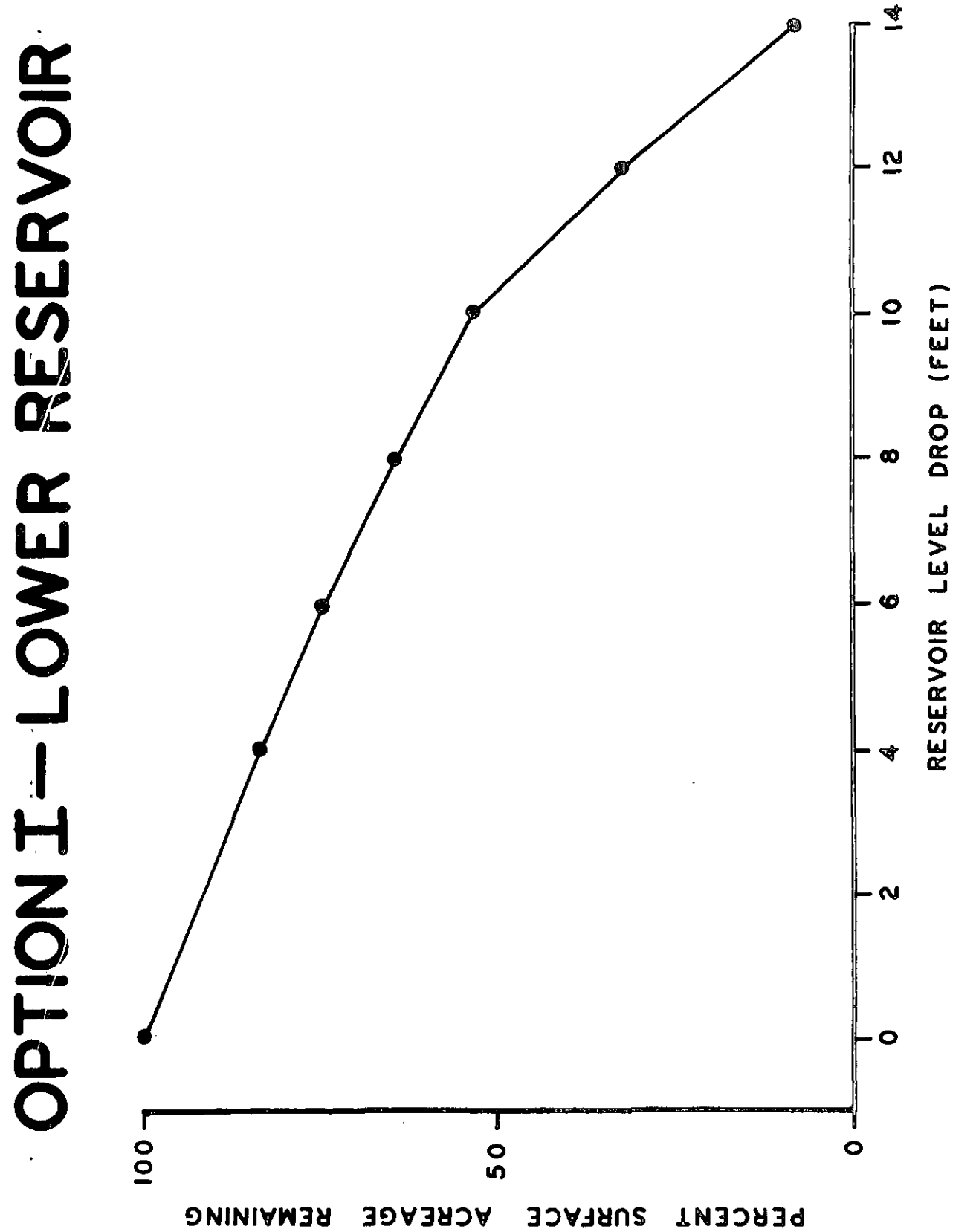
Water Referred to: Madison River Section 1
Key Word: Temperature


OPTION I – LOWER RESERVOIR
PERCENT SURFACE ACREAGE REMAINING
100
50
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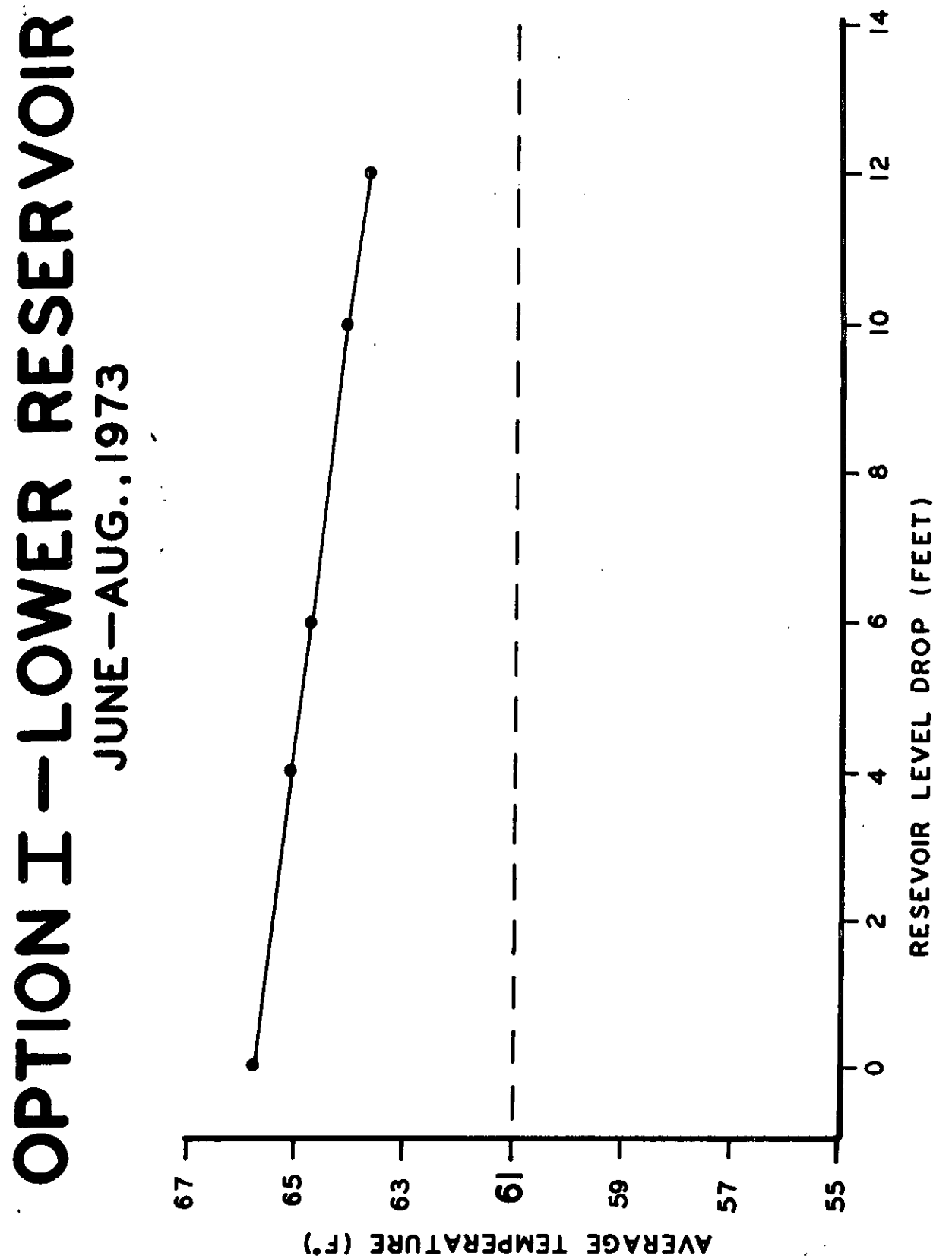
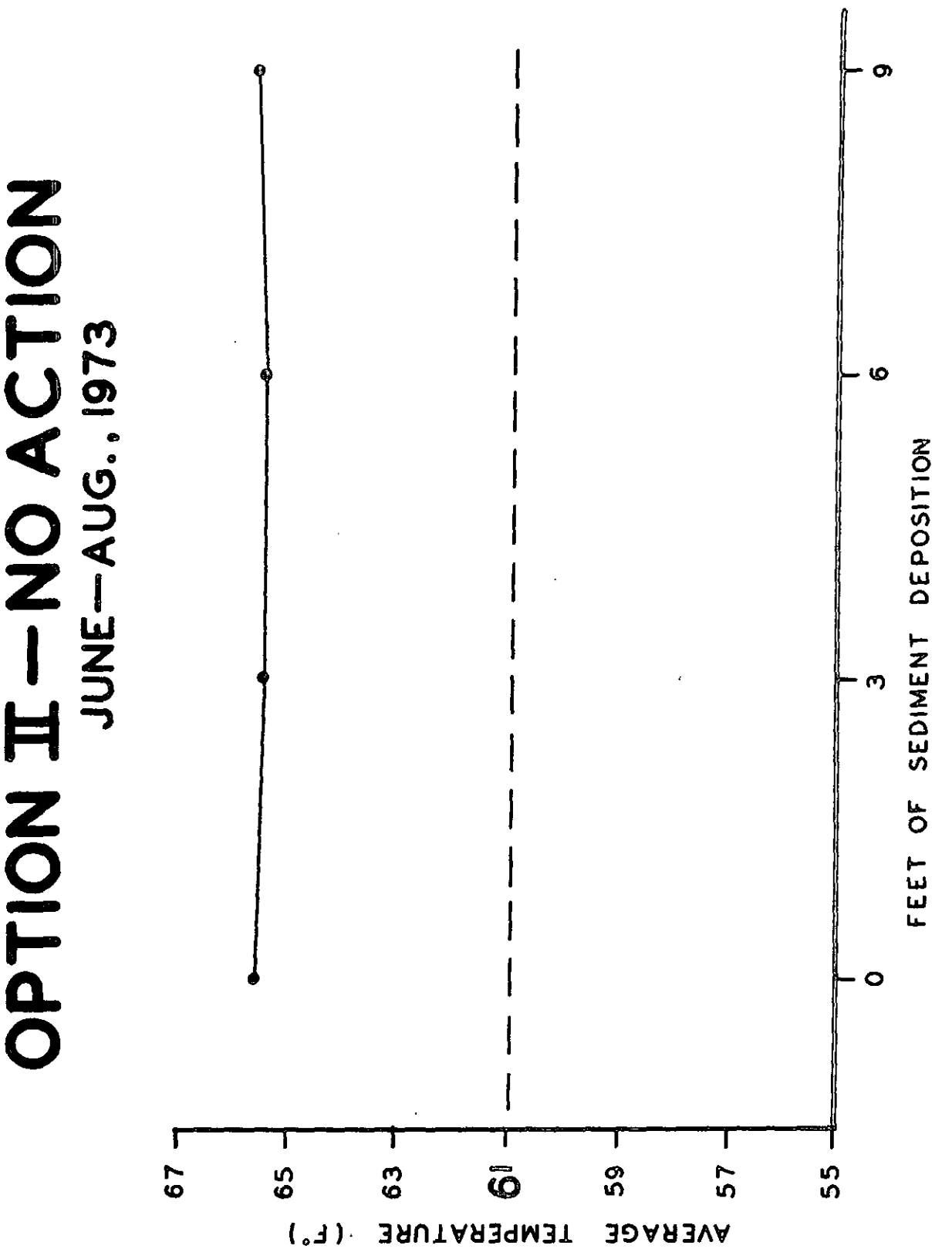
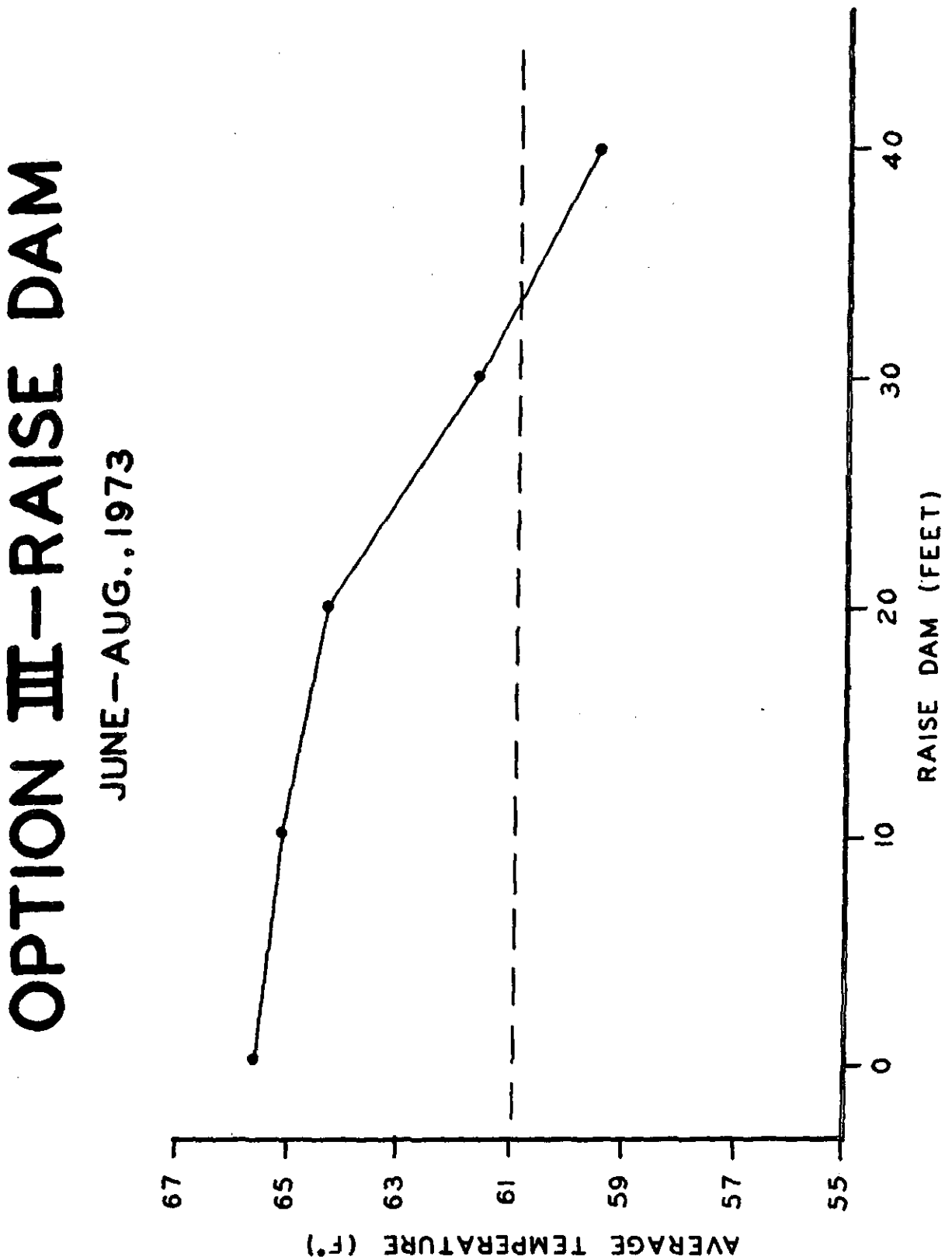
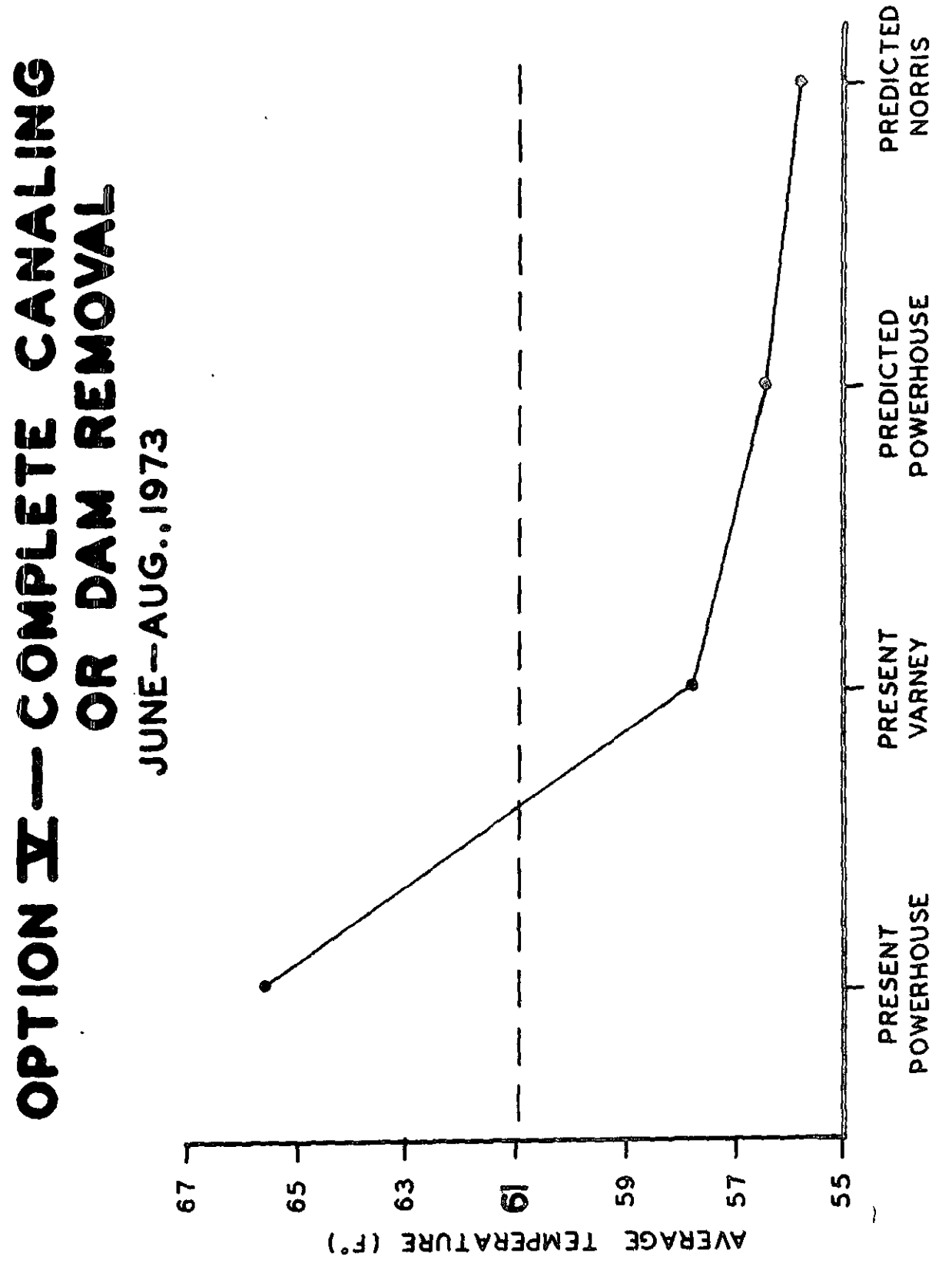
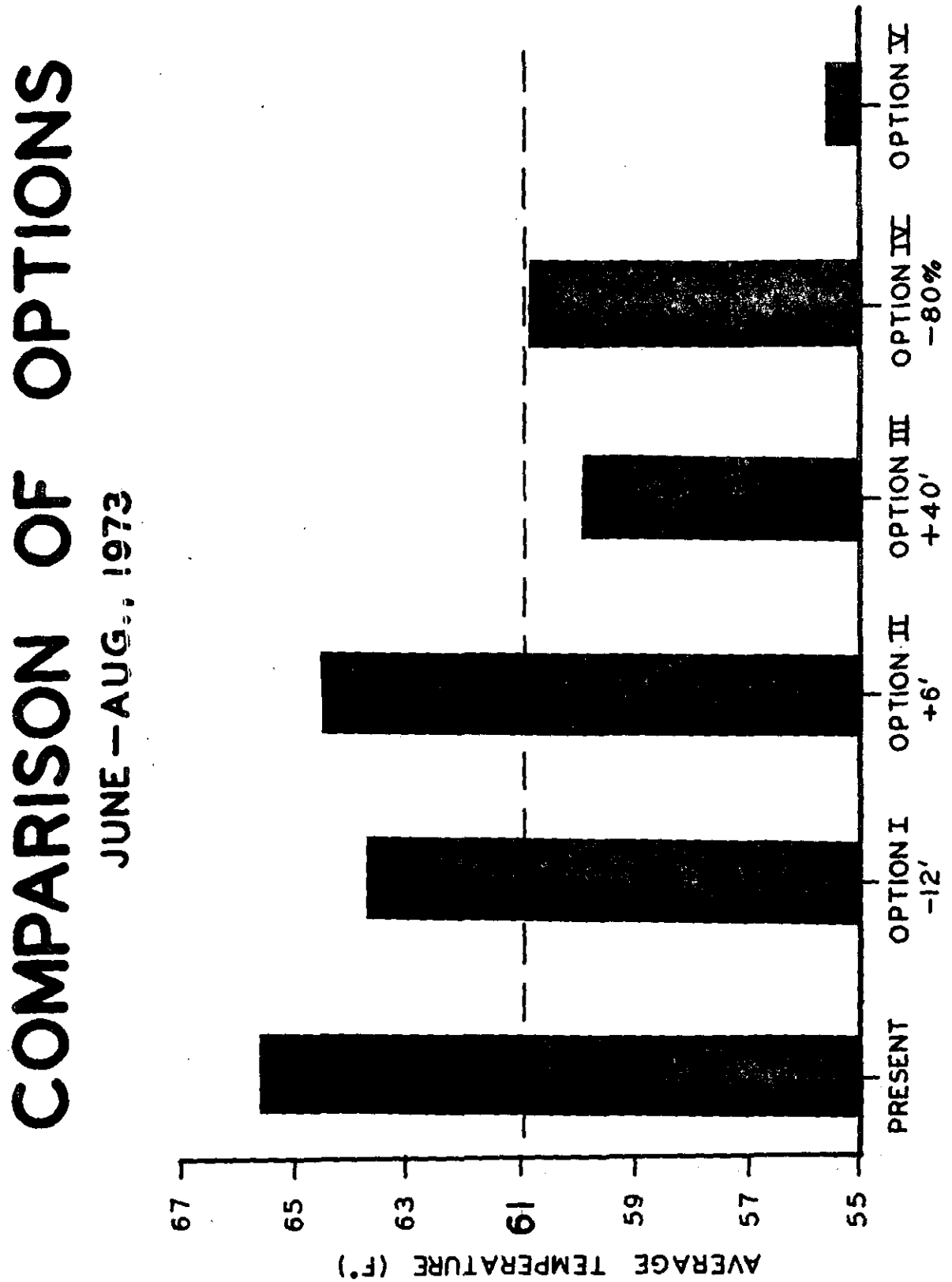
RESERVOIR LEVEL DROP (FEET)
0
2
4
6
8
10
12
14

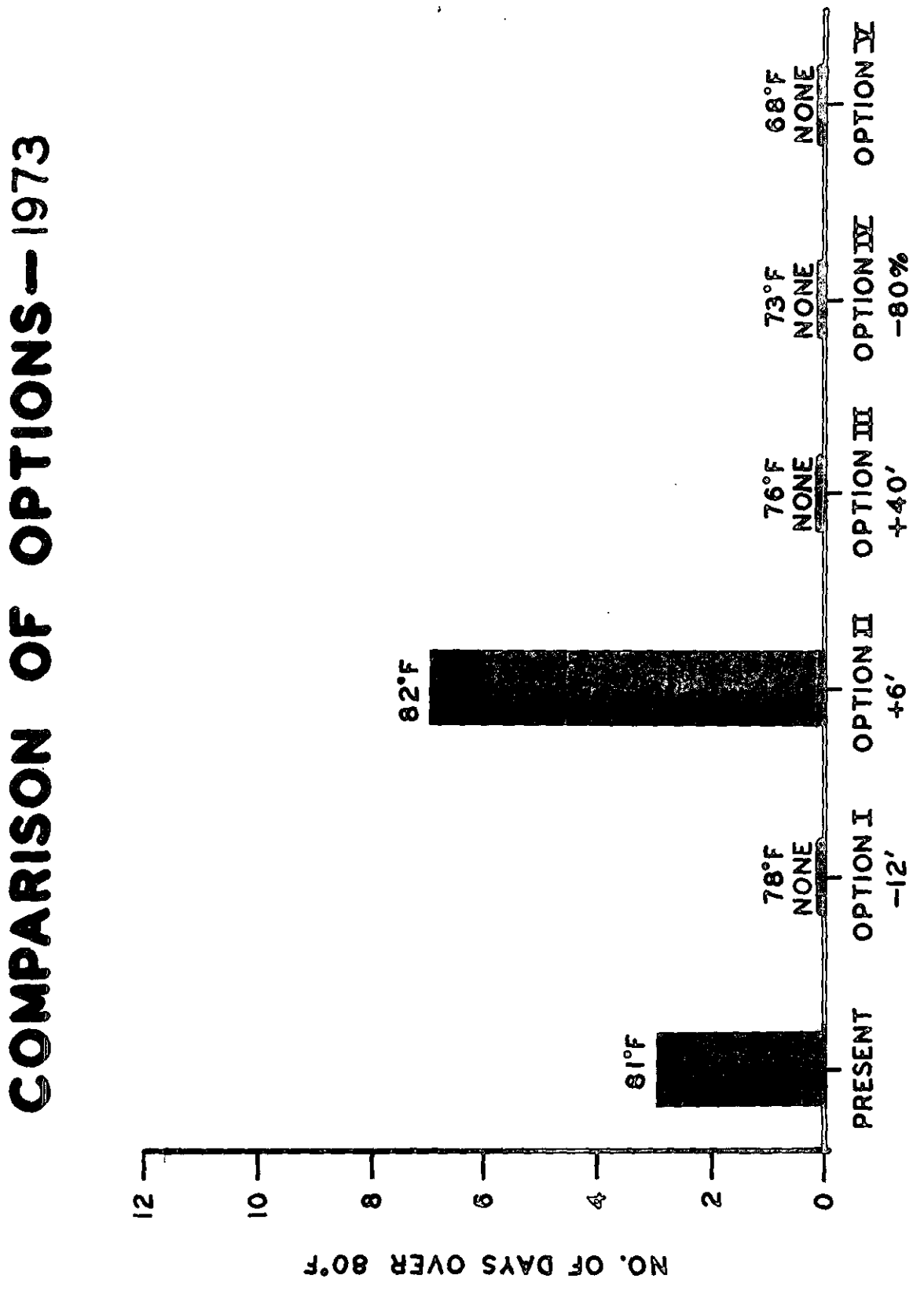

OPTION I - LOWER RESERVOIR
JUNE - AUG., 1973
AVERAGE TEMPERATURE (F°)
67
65
63
61
59
57
55
RESEVOIR LEVEL DROP (FEET)
0
2
4
6
8
10
12
14


OPTION II—NO ACTION
JUNE—AUG., 1973
AVERAGE TEMPERATURE (F°)
67
65
63
61
59
57
55
FEET OF SEDIMENT DEPOSITION
0
3
6
9


OPTION III—RAISE DAM
JUNE—AUG., 1973
AVERAGE TEMPERATURE (F°)
67
65
63
61
59
57
55
0
10
20
30
40
RAISE DAM (FEET)


OPTION II — COMPLETE CANALING OR DAM REMOVAL
JUNE–AUG., 1973
AVERAGE TEMPERATURE (F°)
67
65
63
61
59
57
55
PRESENT POWERHOUSE
PRESENT VARNEY
PREDICTED POWERHOUSE
PREDICTED NORRIS


COMPARISON OF OPTIONS
JUNE—AUG., 1973
AVERAGE TEMPERATURE (F°)
67
65
63
61
59
57
55
PRESENT
OPTION I -12'
OPTION II +6'
OPTION III +40'
OPTION IV -80%
OPTION V


COMPARISON OF OPTIONS—1973
NO. OF DAYS OVER 80°F
0
2
4
6
8
10
12
81°F
82°F
78°F
NONE
-12'
76°F
NONE
+6'
73°F
NONE
+40'
68°F
NONE
-80%
PRESENT
OPTION I
OPTION II
OPTION III
OPTION IV