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Shasta Temperature Control Device Hydraulic and Mathematical Model Studies

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SHASTA TEMPERATURE CONTROL DEVICE

HYDRAULIC AND MATHEMATICAL MODEL STUDIES

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These studies are the product of work by a large group of individuals. The mathematical model studies were conducted by Jack Rowell of Reclamation's mid-pacific (MP) regional office with input from Alan Stroppini, also of the MP regional office, and from the author. Statistical analysis of historic power operations and reservoir data were conducted by Alan Stroppini and Robert Young of the MP regional office. The physical model studies were conducted by the author with direct supervision from Brent Mefford. Strong direction to these studies was given by the design team and, in particular, Mike Kinnan, Rick Christensen, Al Bernstein, and Dick LaFond (the principal designer), all from the Denver Office. Others with significant input include Greg O'Haver and Paul Capener of the Shasta Project Office and Dave Eubank and Colette Diede of the MP regional office.

OVERVIEW

These studies were made to develop a structure that would allow effective management and release of the cold water resource in Lake Shasta with the principle objective of supplying sufficient cool water to the Sacramento River in late summer to prevent temperature-related winter run salmon mortalities. Both mathematical and physical model studies were conducted to evaluate alternative temperature control device (TCD) designs, to define the upper and lower limits of the structure, to size and position intakes, and to verify and refine hydraulic features of the design.

The existing penstock intakes are positioned on the right abutment with a centerline elevation of 815, approximately 250 ft above the reservoir bottom. In particular, in dry years when the reservoir water surface is low, late summer water temperatures at the penstock intakes are too warm to yield acceptable river water temperatures between Keswick and Red Bluff Dams (river temperatures are also influenced by tributary inflows and atmospheric warming). The ideal is to maintain river temperatures at or below 56° F over the full river reach. However, to a greater or lesser degree depending on hydrologic and climatic conditions, warming of river flows will limit conformance to a portion of the reach. With the current penstock intake configuration, water can be drawn from only one elevation. Deeper cold water cannot be accessed for power release.

Various structures (TCD's) which would allow power withdrawal from alternative elevations in the reservoir were investigated. Structures considered included large flexible curtains suspended in the reservoir surrounding the power intakes and rigid steel structures placed over the power intakes and attached to the dam face. These investigations were conducted in support of design efforts which included feasibility evaluations of a broad variety of release temperature control options.

Results of these studies are based on statistical analyses of reservoir water surface elevation and power operations, projections of future operation, reservoir and river mathematical model studies, physical model studies of alternative TCD designs, and selective withdrawal theory.

CONCLUSIONS

1. A rigid TCD offers an effective way to manage water supplies in Lake Shasta with the objective of improving water temperatures in the upper Sacramento River. This finding was confirmed by both mathematical and physical model studies. The proposed rigid shutter device includes optimum flexibility for release control. The alternative curtain concept also appears to be effective although its hydrodynamic characteristics are more complex.

Mathematical Models

2. Adding deep water access to the existing power intakes will yield river cooling for a limited time duration in low water years. In years such as 1988 (a low water year that would occur approximately every 10 years), the addition of deep water access reduces the length of time that release and river water temperatures exceed the basin plan water quality objectives. However, maximum release temperatures will equal or exceed historic release temperatures made through the existing intakes. The problem is that if releases are made through the existing intakes until river temperatures exceed criteria and then deeper water is accessed, in lower water years insufficient cold water reserves are available to meet late summer and early fall water demands.

3. Use of a TCD that allows high-level withdrawal (from elevation 950 to 1045) early in the season and deep withdrawal (from elevation 650 to 750) later in the season offers optimum potential for release and river cooling. By releasing from high in the reservoir during spring, river temperatures which are 1 to 2°F warmer than historic can be achieved. This is of benefit in that historically spring river temperatures are too cold for optimum incubation and fish growth. High level releases allow cold water reserves to be saved and used to achieve significant release and river cooling during the late summer and early fall. In 10 percentile low water years (like 1988), late summer release temperatures can be reduced by 5°F with resulting 1 to 4°F reductions in river temperatures. In 3 percentile low water years (like 1976), mid-summer release

temperatures could be reduced by 10 to 12°F with up to 6°F reduction in river temperatures. However, in these critical low water years, even with optimum cold water management, insufficient cold water reserves would be available to sustain cold water releases through the late summer and fall. Consequently, either late summer and fall release temperatures would rebound and be comparable to historic temperatures or early summer releases would have to be managed for something less than optimum river temperatures. In high water years (such as 1975, approximately the 75 percentile), use of high and low TCD intakes would allow river temperatures at Cottonwood Creek to be sustained at temperatures below 56°F throughout the summer and fall and would allow a water temperature at or below 57°F to be maintained at Red Bluff.

4. Access of the deep cold water reserves (that cannot be accessed with the existing power intakes) is of particular importance in extreme low water years. Conservation of cold water reserves through use of high level intakes in the spring significantly improves performance in all years. Use of high level TCD intakes with the existing 815 power intakes (but with no deep water access) produces comparable release temperature control to a TCD with both high and deep intakes in years when reservoir elevations are equal to or higher than those of 1988 (approximately 10 percentile low water year). This reflects the importance of using the high level withdrawal in the spring and conservation of large volumes of cold water. However, in critical low water years, up to a 5°F release cooling and 2°F river cooling for a 1- to 2-month period is lost if deep intakes are not included.

5. Two levels of intermediate gates (between the upper and lower intakes of the TCD) allow desired control of release temperatures. Several arrangements of intermediate gates (between the upper and lower intakes of the TCD) were studied. Up to four levels of intermediate gates were considered. It was found that including numerous levels of intermediate gates did not improve TCD performance. Use of two levels of intermediate gates (between 900 and 945, and between 800 and 827) is recommended.

6. The top of the TCD should be positioned above frequently occurring reservoir high water elevations to prevent overdraw generated by flow entrainment within the TCD. Based on reservoir math model findings, raising the top of the TCD from elevation 950 to elevation 1045 in an effort to further increase cold water reserves does not significantly improve TCD performance. However, physical model study findings show that internal mixing and flow generated head losses within the TCD will cause entrainment of high level withdrawal (overdraw) water into the release (even if the objective is to withdraw totally through the low level intakes). This is particularly the case at higher discharges. Findings indicate that to totally exclude overdraw, a physical blockage should be used (buoyancy in itself will not do the job). One option is to extend the top of the TCD to or above the reservoir surface to obtain this control.

7. Because of operational limitations, it is recommended that the TCD structure be placed over all five power intakes. Based on 1988 (10 percentile low water year), if the TCD was placed over only three intakes, only a slight reduction in temperature control performance would result. This assumes that the TCD modified units would be the first used and that the unmodified units would be used only for peaking. Thus, placement of the TCD over a limited number of units would change operating procedures. Likewise, temperature control would suffer if modified units were down for maintenance. For this reason, placement of the TCD over less than all five units was not further considered.

8. Again because of operational limitations, deep water access capabilities should be available for all five units. Having deep water access capabilities with three units produced comparable performance to having deep water access capabilities with all five units, even in low water years. If deep water access was limited to two units, river warming of 0.5 to 1°F would result (as compared to five unit access). If deep withdrawal is limited to one unit, warming of 1 to 1. 5°F would result (particularly in low water years). If individual units were modified for deep water access, then the same operational restrictions mentioned above would occur. Historic operation shows that in late summer and fall, simultaneous use of more than three units will generally not occur.

Physical Model - Curtain

9. Differential pressure loads of up to 15 lbs/ft^2 can occur across a large curtain TCD. Maximum differential pressure loading on large curtain TCD's occurs when the curtain is operating with total overdraw. With total overdraw, the zone between the curtain and the dam is filled with warmer water while the bulk of the reservoir profile remains cold. This difference in profiles maximizes density-generated loading. Differences between the predicted and vertically integrated model profiles indicate the potential for pressure differentials across the curtain to exceed 15 lbs/ft^2. When this load is applied over the large surface area of the curtain, the density-generated loading becomes a major design consideration.

10. If properly operated with low overdraw and underdraw velocities, dynamic head losses across large curtain TCD's are less than 0.02 ft of water at 17,600 ft^3/s.

11. Substantial three-dimensional mixing occurs between the curtain and the dam. This mixing not only influences temperature profile shifts across the curtain (which in turn influences density loading), but also causes entrainment of underdraw and overdraw flows into the releases. For example, if the objective is to release solely deep cold water and if the top of the curtain is submerged (thus the curtain does not supply a physical blockage to overdraw), underdraw currents generated will mix with and entrain overdraw flows amounting to at least 10 to 20 percent of the total release. It is possible that by increasing intake areas and thus reducing flow velocities, entrainment could be reduced.

Physical Model - Rigid TCD

12. Depending on operation, maximum head loss (at a discharge of 19,500 ft^3/s) across the rigid TCD can vary from less than 0.1 ft of water to approximately 2.2 ft of water. Head losses across the rigid TCD are a function of discharge and intakes used. When operated solely in overdraw, head loss is also a function of submergence of the top of the structure.

13. Vertical mixing inside the rigid TCD is limited by the near proximity of the TCD walls. As a result, temperature gradients inside the TCD, when intake flows from different sources merge, are more abrupt than with the curtain. Consequently, the temperature profile inside the TCD can be predicted fairly accurately if the reservoir temperature profile and the intake gates used are known.

14. To allow total underdraw over the full potential discharge range in all but very high water years, the top of the TCD should be positioned at elevation 1045. Head losses and mixing associated with 720 underdraw for discharges greater than 8000 to 10,000 ft^3/s will likely cause entrainment of overdraw flow (if the top of the TCD does not extend to the surface and block the overdraw). At the 1045 elevation, the top of the TCD will be at or above the reservoir surface in 75 percent of the years in July, 90 percent of the years in August, and 85 percent of the years in September (based on historic data and 1985 water demand). To exclude overdraw at high discharges when the top of the TCD is submerged, intermediate level gates should be used in combination with the 720 intake.

15. Depending on submergence and discharge, a potential exists to draw air into the penstocks when the TCD is operated in a total overdraw mode or when gates with shallow submergence are used. Entrained air may yield either blowback or rough turbine operation and thus should be avoided. Although the physical model scale was not ideal to set submergence criteria, it is currently recommended that with a maximum discharge of 17,600 ft^3/s the upper gates should be lowered when the reservoir elevation drops below 1059 (elevation 1065 with a maximum discharge of 19,500 ft^3/s). When submergence on the lowered upper gates is less than 30 ft, the next lower level of gates (or at least a portion of the next lower level of gates) should be opened. Minimum submergence criteria is based on maximum discharge and assumes that gate position will not be changed with daily peaking (the gate design also will not allow changes in gate setting with plant peaking). It is recommended that this criteria be reviewed and modified, if needed, through observation of the operating prototype structure.

16. The distribution of withdrawal between multiple levels of simultaneously used TCD intakes can be computationally evaluated knowing reservoir temperature profile, elevations of withdrawal, and total discharge. Density and head loss influences are determined and considered in obtaining the flow distribution. An example calculation is provided within the report.

17. A withdrawal layer predictive equation which has been fit to the Shasta site with the rigid TCD predicts, for a September 1988 reservoir profile, that the volume of unaccessed water (the volume of cold water that could not be accessed and released in late summer) varies from 27,000 acre-ft at a discharge of 4000 ft^3/s to 7200 acre-ft at a withdrawal discharge of 19,500 ft^3/s. An experimentally developed equation (Smith et al.) which predicts withdrawal layer thickness as a function of reservoir temperature profile, intake elevation, and withdrawal discharge has been modified to reflect topography and structural influences observed in the physical model. Predicted volumes of unaccessed cold water are conservatively high in that a shear exists between the withdrawal layer and the cold water below. This shear in conjunction with the mixing influence of the peaking operation should mix and gradually entrain the deeper water into the withdrawal.

APPLICATION

The specific results of the math model and statistical studies cannot be directly applied to other sites. The results of these studies are strongly dependent on power operations, structure configuration, climatic conditions, and hydrologic conditions; all of which tend to be site dependent. The results from the math models and statistical model may give some general insight into similar conditions at other reservoirs and dams and may provide initial direction to studies of other structures with similar problems. The results of the hydraulic model study have broader application in that they define and confirm the influence of various factors on structural performance and give direction to determine loads on the structure. The results also define the performance limitations of the structure concepts considered. Thus, for structures of similar design to those studied, if operating conditions and expected reservoir profiles are known, the results of the hydraulic model study can be used computationally to predict structure influence on releases. Limitations on structure performance and loading on the structure can also be predicted.

INTRODUCTION

The Sacramento River system is the largest in California yielding 35 percent of the state's water supply and providing the most important salmon habitat in the state. Chinook salmon from the Sacramento River account for 80 percent of the commercial catch from San Francisco to Monterey, 40 percent of the North Coast catch, and 5 percent of the Oregon catch. Since the early 1970's, the chinook salmon population in the Sacramento River has been on the decline. Numerous studies and corrective actions have been undertaken by State and Federal agencies to protect and enhance the fisheries.

River temperatures are one of the most critical factors limiting habitat. Table 1 shows desired temperature ranges for various chinook life stages.

Table 1. Preferred water temperatures for various chinook salmon life stages

Life Stage	Preferred Range	Comments
Spawning	42 - 57	
Incubation	43 - 58	* temperatures in excess of 58 begin to be lethal * temperatures in excess of 62 yield 100 percent mortality
Juvenile rearing	45 - 58	* 54 is optimum * temperatures in excess of 58 begin to be lethal
Adult migration: General Fall Spring	 49 - 57.5 51 - 67 38 - 56	

As shown in figure 1, four major runs occur on the Sacramento River. Fish are present, spawning, incubating, and rearing in the river year-round. At present, chinook salmon in the Sacramento River are adversely impacted by water temperatures that are too warm during the summer and fall for optimum egg and fry survival, and too cold during the spring months for optimum growth. Due to large declines in the population of winter run chinook, the National Marine Fisheries Service (NMFS) has placed the species on the threatened species list.

Construction of Keswick Dam (the re-regulation dam for Shasta and Spring Creek Powerplants) and Shasta Dam truncated the salmon runs on the mainstem Sacramento. Significant spawning now occurs on the river between Red Bluff and Keswick Dam a distance of approximately 60 river miles. Figure 2 is a map of the upper Sacramento drainage showing major structures that influence river flows and water temperatures.

Shasta Dam is a 607-ft-high concrete gravity structure which was completed in 1945 (figures 3 and 4). It serves to control flood water, store surplus winter runoff for irrigation and domestic use, provide maintenance of flow for navigation and conservation of fish, protect the Sacramento-San Joaquin Delta from intrusion of saline ocean water, and generate hydroelectricity. The dam includes an extensive outlet works structure with intakes at elevation 942, 842, and 742. The dam has a gated spillway with a crest elevation of 1037. The power penstock intakes sit on the right abutment with a centerline elevation of 815, approximately 250 ft above the bottom of the reservoir. The powerplant includes five turbines with a rated capacity of 539 MW.

Currently, units are being upgraded with future additional upgrades expected. The current discharge capacity of the powerplant (which is net head dependent) is 17,600 ft^3/s. Expected upgrades will increase the discharge capacity to 19,500 ft^3/s.

Shasta Dam and Reservoir is the largest storage facility in the drainage with a capacity of 4,500,000 acre-ft and a maximum depth of 490 ft. It is the primary source of flow for the reach of river of concern. Shasta Powerplant is operated in a peaking mode with releases varying hourly, daily, and seasonally as a function of power and water demand. Table 2 statistically summarizes historical plant operation. In the late summer and fall, significant additional flows are also diverted from the Trinity River and Clair Engle Reservoir through Whiskeytown Reservoir and Spring Creek Powerplant to Keswick Reservoir and the Sacramento River. Also, several minor tributaries contribute to the river between Keswick and Red Bluff. The diverted and tributary flows influence both river discharge and river water temperature.

Lake Shasta receives its largest inflows during winter and spring storm events and with snow melt runoff. Inflows during these periods are turbid. The turbidity is caused by very fine sediment which settles and clears over weeks and months. Control of turbidity in releases is a secondary objective of these studies.

As shown in table 2, heaviest draw on the reservoir occurs during the late spring and summer. During this period, the reservoir water surface falls and the water in the upper levels of the reservoir warms due to climatic and inflow influences (figure 5 summarizes historical variations in water surface elevation both monthly and yearly). Figure 5 also shows monthly variations in the reservoir temperature profile. In most years, but in particular in low water or drought years, the water at the penstock intakes warms substantially through the summer months. When this warming is coupled with downstream warming in the river (due to atmospheric and tributary influences), by August, optimum water temperatures may be exceeded over portions of the river reach of concern. River water temperatures can be lowered by accessing and releasing deeper, colder water from Lake Shasta. Currently this requires use of the low level (elevation 742) outlet works which bypass the turbines and result in lost power revenues. Replacement power must then be purchased by the Western Area Power Administration (WAPA) from alternate sources due to contractual commitments. This was done in 1987, 1988, and 1989 with a total cost of approximately $6 million.

Table 2. Probability of "at least" the indicated number of generators in use at any one time by month.

Average Probabilities by Month					
	Number of generators in use at any one time				
Month	1	2	3	4	5
	Average Probability				
1	0.945	0.760	0.472	0.207	0.042
2	0.968	0.779	0.470	0.222	0.090
3	0.971	0.815	0.545	0.299	0.126
4	0.986	0.888	0.644	0.315	0.079
5	0.995	0.954	0.810	0.501	0.155
6	0.998	0.980	0.885	0.608	0.196
7	0.999	0.988	0.922	0.704	0.236
8	0.994	0.940	0.755	0.435	0.107
9	0.901	0.651	0.333	0.103	0.015
10	0.850	0.574	0.284	0.089	0.012
11	0.935	0.689	0.406	0.178	0.045
12	0.948	0.708	0.460	0.285	0.135

Reclamation has conducted studies to identify and evaluate ways to both manage cold water reserves in the reservoir and access deeper cold water for power release. A value engineering study completed in November of 1987 identified several structural alternatives (1) that would function as TCD's. One option identified was a flexible curtain supported by a cable and float system. This option allowed operation with the bottom of the curtain attached to the bottom of the reservoir or with the bottom of the curtain lifted off of the reservoir bottom. By coupling an adjustable bottom with an adjustable curtain top, control of the elevation of withdrawal and access to deeper cold water appeared possible. A second option considered was a steel structure attached to the dam and placed over the trashrack structures and penstock intakes. This structure was gated at various elevations which allowed selection of the elevation of withdrawal and access to the deeper water.

For all the TCD concepts considered, the performance capabilities of the device (with respect to supplying water of the desired temperature) and the static and dynamic loading on the TCD are in part dependent on the reservoir temperature stratification, on the withdrawal characteristics of the TCD, and on vertical mixing and head loss inside the TCD. Reservoir temperature stratification and how it varies as a function of hydrologic conditions, climatic influences, and elevation and magnitude of withdrawal is best studied using reservoir computer models. The reservoir computer model, WQRRS (2), which uses monthly average inflows, outflows, and climatic conditions, was used in this study. The model had been previously applied to Lake Shasta with its accuracy verified by historic data. The reservoir model was used to evaluate various TCD designs and operations to determine both the influence of the device on the reservoir (which in turn effects the performance of the device later in the year) and the influence of various hydrologic and climatic years on the reservoir and, in turn, on the TCD performance.

The hydraulic characteristics of the various TCD concepts are complex. Factors to be considered include intake coefficients, internal head loss, density influences on vertically displaced flows, vertical mixing and flow entrainment, and resulting density profiles inside the TCD and their influence on net head differential across the structure. The three-dimensional flow problem that the TCD presents is best addressed using a density stratified physical model. Consequently, a 1:72 scale model (which is described later) was constructed and tested in the Water Resources Research Laboratory (WRRL) of the Denver Office.

Also of concern was the downstream influence of the TCD operation on river temperatures between Shasta Dam and Red Bluff. As previously noted, resulting river temperatures are a function of release temperatures and discharge magnitudes at Shasta Dam, diversion and tributary flow temperatures and discharge magnitudes, river morphology, and climatic influences. A release discharge and temperature that easily meets downstream temperature requirements in May could fall well short of meeting the requirements in August.

Again, the best available tool for analysis of this flow and determination of water temperature at various river stations is a computer or mathematical model. A Reclamation developed model (3) which had previously been applied to and verified for this reach of river was used. Use of this model shows the downstream influence of various TCD designs and operations. It also shows the limitations of downstream temperature control that can be achieved through use of the TCD.

THEORY

Withdrawal Layer - When a reservoir is density- (and water quality-) stratified, it is possible to withdraw water from distinct layers. The vertical position and thickness of the withdrawal layer depends on the vertical position of the intake, the size and orientation of the intake, the withdrawal discharge, the density stratification profile, and reservoir geometry. Positioning intakes at various elevations in the reservoir allows selection of the horizontal layer from which water is withdrawn. Numerous studies have been conducted to define upper and lower bounds and thus the vertical thickness of the withdrawal layer (4,5,6,7). These studies were done in stratified laboratory reservoirs (typically in rectangular flumes) with simplified intake and reservoir geometry. The laboratory findings have been at least generally confirmed by field observations. There are, however, variations between theories which indicate uncertainties. In addition, secondary currents and site-specific geometry-influenced flow features are generated in Shasta Reservoir that do not occur in laboratory flumes. Thus, variations away from the withdrawal layer bounds predicted by simplified theory can be expected. However, it should be noted that the reservoir math models used in this study have been fit to Shasta Reservoir based on field data. Thus, the withdrawal layer theory included in these models has been adjusted to give a true representation.

The following are two of the available withdrawal layer equations. They give a feel for parameter interrelationship and variations in layer thickness prediction. Smith, et al. (4), characterize the withdrawal layer with the equation (see figure 6):

$$\frac{Q}{\sqrt{\frac{g}{p}\frac{dp}{dz}h^6}}=1.0$$

Where:
- Q = The withdrawal discharge through the intake
- p = Reservoir water density at intake centerline elevation
- h = Half withdrawal layer thickness from intake centerline to either the upper or lower bound
- g = Gravitation constant
- z = Vertical coordinate

The above equation is appropriately applied when the intake dimensions are small as compared to total reservoir width and depth, when approach geometries to the intake are not constricted, and when the vertical density gradient in the reservoir is linear (this is never the case, but the equation allows for consideration of density gradient influences). Note that when the density gradient (dp/dz) is small or approaches zero, the resulting withdrawal layer thickness is large. In the extreme, for a fully mixed or

homogeneous reservoir, the thickness of the withdrawal layer is the full reservoir depth. Likewise, when the density gradient is large (in zones with strong vertical temperature change) the resulting thickness of the withdrawal layer is reduced. As can be seen in the equation, the layer thickness to the sixth power is inversely related to the density gradient. Thus, if the density gradient increases by a factor of 64, withdrawal layer thickness will be halved. Discharge also influences withdrawal layer thickness with larger discharges yielding greater thickness. In the extreme, large discharges can yield withdrawal from the full reservoir depth. Again note from the equation that discharge is linearly related to the cube of the layer thickness or that an eight-fold increase in discharge will yield a doubling of layer thickness.

A second equation developed by King (7) allows a more detailed consideration of significant parameters.

This equation:

$$\frac{D^4 p V^2}{g} = dpK^2 h^3 W^2$$

Where:
- D = Intake diameter for a compact (square or circular) intake
- p = Reservoir water density at intake centerline elevation
- V = Flow velocity in intake
- g = Gravitational constant
- K = Coefficient that is dependent on intake shape (approximately equal to 0.4 for a compact intake)
- h = Withdrawal layer half-width from the intake centerline to either the upper or lower bound
- W = Reservoir width at intake centerline elevation

The above equation allows consideration of more restrictive reservoir and intake geometries. Thus, the equation can be applied to a broader range of intake sizes and shapes than the first equation presented (within the limits that either a defined value of K is available or can be developed for the particular intake being considered). Likewise, the equation can be applied in situations where a small or restrictive reservoir geometry exists (the equation shows withdrawal layer thickness to be an inverse function of reservoir width to the two-thirds power). In the equation, note that the half-width (h) appears as a cubed function but the cubed half-width is presented as being proportional to the square of the discharge (D^2V) and inversely proportional to the density differential across the half layer (dp).

Comparison of computed withdrawal layer thickness (using both of the above equations) for discharges of 3000, 6000, 9000, 12,000, and 15,000 ft^3/s are presented in figure 7. The layer thicknesses were computed based on a predicted September 1988 reservoir temperature profile (predicted by a math model in which progressive releases were made from the 950, 920, 890, 860, and 720 levels to optimize river temperatures). As can be seen, this profile has a strong temperature gradient at the 720 level which restricts withdrawal layer thickness. As previously noted, the computed withdrawal layer limits for both equations are based on idealized intake and topography geometries. Layer thicknesses computed based on the King equation were predicted for an intake diameter of 86 ft (intake velocity of 3 ft/s at a discharge of 17,600 ft^3/s) and a reservoir width of 700 ft (the approximate width of Lake Shasta at the 720 level). Note that there is substantial disagreement between the two equations which defines a range of uncertainty. Note also that with a reduced reservoir width the two equations could agree. Comparison to reservoir profiles predicted monthly by the math model shows a better agreement with the Smith equation in that the math model shows influences of withdrawal from the 720 level which extend down to nearly elevation 600. Since math model predictions have been confirmed by field observations, it indicates that the Smith equation results might be more representative of actual field conditions. Again, however, the King equation is useful in that it shows intake and reservoir geometry influences. Finally, note that the Smith equation predicts mean withdrawal to approximately elevation 620. Remaining reservoir storage below this level is very small, approximately 2500 acre-feet. Withdrawal layer bounds were also directly observed in the physical model. The observed withdrawal layers include structure and topography influences. Observed layer thicknesses with a comparison to and adjustment of the theory-based computed bounds are presented later in this report.

Temperature Control Device - The TCD (curtain or rigid structure) placed in front of the power intakes will typically modify the vertical position of flow withdrawal away from the centerline (elevation 815) of the existing power penstock intakes. Use of the TCD may yield withdrawal from one elevation or from multiple elevations depending on TCD intakes used. In either case, withdrawal layers will be generated at each withdrawal point. These withdrawal layers may be independent or they may overlap. The withdrawal layer theory presented above can be used to define the resulting layers. The influence of overlapping layers is superimposed.

When wicket gates are opened and a discharge is initiated through a turbine or turbines, a discharge through the TCD is also initiated. Depending on gate or orifice openings in the TCD as well as gate and orifice coefficients and internal losses (due to structure geometry, structural members or internal roughness, and internal flow constrictions), a net head loss associated with the particular discharge and particular flow path results. If multiple levels of gates or orifices are open in the TCD, then multiple flow paths from the reservoir to the penstock intakes exist. However, the energy available to move the flow from the reservoir to the penstock intakes on any of

the flow paths is a constant. In addition to head losses, energy may be required to either lift cold dense water up to the penstock intake or pull warm buoyant water down to the intake. Figure 8 shows a TCD operating with total overdraw and the corresponding temperature shifts that would result. The head required to overcome buoyant effects and pull the warm surface water down to the intake equals the difference between the pressure head at the 815 elevation in the reservoir and the pressure head at the 815 elevation between the TCD and the dam. The pressure head is obtained by integrating the product of the water density and the vertical depth increment from the water surface to the 815 level. A numerical integration with resulting differential is shown on figure 8.

Traditional selective withdrawal structures are vertical or inclined closed conduits with gated intakes at various elevations. The elevation or elevations of withdrawal are selected and controlled through use of the gates. However, most of the TCD alternatives considered for Shasta, when submerged, are open to the reservoir at the top. This is because either it is impractical to enclose the top of the TCD (as with the large curtain concepts) or that by enclosing the top, excessive transient loads are created inside the TCD with start-up and/or load rejection. With an open top there is no structural means to exclude flow when the top of the TCD is submerged. Overdraw could be structurally excluded when the reservoir water surface drops below the top of the TCD. To obtain positive control with an open-topped structure, the TCD could be extended to higher elevations yielding a positive barrier at all but the highest reservoirs. During high water years, large quantities of cold water are available and thus total exclusion of overdraw and optimum management of cold water reserves would likely not be required.

Alternative operations for the open-topped TCD's when submerged include total overdraw with all intermediate and low-level intakes closed, predominately intermediate-level withdrawal with intermediate level intakes (when available) open and with low-level intakes closed, predominately low-level withdrawal or underdraw which would occur with warm surface water and with intermediate-level gates closed while the low-level intakes are full open, and a blended or mixed release (which would depend on the reservoir temperature profile and on low and intermediate intake openings). A discussion of each of these operations follows.

Total overdraw except for leakage is achieved by operating the TCD with the top submerged and with intermediate and low-level intakes closed. All water is withdrawn from the reservoir at the top of the TCD and passes downward inside the TCD to the penstock intakes. The top of the TCD functions as something between an upward facing intake (which is more the case for smaller TCD's that are near the dam) and a submerged weir (which is more the case for the large curtain concepts) . A recently published paper by Goldring (8) indicates that the vertical (or upward facing) orientation of the intake will cause the intake to draw from higher in the reservoir. In

this case, a virtual centerline that is above the top of the TCD might be used in withdrawal layer computation. This means that for small TCD structures positioned near the dam, overdraw will yield warmer releases than the top elevation of TCD might indicate. The upward orientation may in effect extend the vertical influence of the TCD which is not necessarily a negative feature. When overdraw release temperatures exceed desired levels, lower intakes can be used.

Operation of the TCD in overdraw fills the zone between the TCD and the dam with warmer water. The resulting temperature profile between the TCD and the dam depends on the particular TCD concept. With the larger curtain structures (figure 9), if the withdrawal layer does not extend to the surface, a shear will occur between the withdrawal layer and the warmer water above it (figure 10). This shear pulls the warm surface water toward the dam. The water accumulates between the TCD and the dam as a thickened surface layer (figure 10). The withdrawal layer flow passes over the top of the curtain and then, because it is cooler than the thickened surface layer, it falls or plunges (figure 10). When the plunging overdraw reaches water of equal temperature and density, a submerged hydraulic jump occurs. A mixing zone thus results below the thickened surface layer (figure 10). Some entrainment of surface water into the withdrawal flow occurs with this action. The water from this mixed zone is then passed through the 815 intakes. These flow conditions were observed in the physical model. Examples of model-observed shifts in temperature profile, due to this flow pattern, are shown in figures 11 through 14. Figure 11 shows curtain-generated profile shifts that occur with total overdraw and less leakage (note the strong temperature shifts). Figure 12 shows the temperature shifts that result with a high reservoir and with the bottom of the curtain raised (the majority of the flow is underdraw and thus the profile warming shift generated by the overdraw is weak; also, due to the large flow path area over and under the curtain, head losses and required temperature shifts are very small). Figure 13 shows profiles associated with combined overdraw and underdraw and with approximately 30 ft of submergence over the top of the curtain (a moderate temperature shift results, which generates a balance between underdraw and overdraw). Figure 14 shows a curtain operating with underdraw and overdraw potential but with a very shallow submergence (note that this approaches a density blockage where temperature shifts generate sufficient head to create a strong underdraw with very little overdraw).

Smaller TCD's which are rigid or which contain rigid elements (figure 15) produce similar profile shifts; however, mixing is more controlled and thus temperature gradients inside the TCD are more abrupt then those observed with the large curtains. Thus, the plunging action with the thickened surface layer is less pronounced and very strong temperature gradients tend to result at the elevation of the existing power intakes. Profiles similar to those shown in figures 16 through 18 result. For either type of TCD and for the various potential operating conditions, the temperature profile shifts yield modifications to the net differential loading on the TCD. This net loading is evaluated by adjusting head loss and/or transient-generated loadings by the difference between the vertically integrated density profiles.

When overdraw flow temperatures exceed desired levels, lower intakes are opened. For rigid structure concepts, this means opening lower gates. For flexible curtain concepts, this means either lowering the short curtain panel between the head tower and the dam or lifting the bottom of the curtain. The result may be that withdrawal would occur from two levels simultaneously. When this happens, the distribution of the withdrawal discharge between multiple intakes is a function of the energy equation which, for the TCD's, could be formulated as:

$$E = v^2/2g + \text{Sum}\ (dp)\ (dy) + \text{losses}$$

Where:

E	=	Available energy to move the flow from the reservoir to the 815 intakes
V	=	Upward or downward velocity at the 815 level between the TCD and the dam
g	=	Gravitational constant
dp	=	Incremental vertical density difference
dy	=	Incremental vertical distance
losses	=	Head losses on the flow path between the reservoir and the 815 intakes (this term is largely a function of flow velocity at the TCD intake, exit losses which result when the flow from the TCD intake enters the zone between the TCD and the dam, and geometry and roughness-related losses on the flow path between the TCD and the dam)

In the above equation, one or all of the included components may prove significant. For example, for structures where the TCD is placed close to the dam, flow velocities and thus velocity heads for the flow between the TCD and the dam may be a significant component of the energy equation. On the other hand, for the large curtain concepts where the flow path area is very large and velocities are low, the velocity head term will be insignificant. For most concepts there are operating situations for which integrated density terms will be large and thus density influences on the withdrawal distribution would be important. For example, it is possible that the buoyancy of warm surface water may prevent overdraw (density blockage) and yield a dominant underdraw even though both underdraw and overdraw flow passages are open. Thus, density may be used to achieve overdraw control which could not be otherwise achieved with an open-topped structure. Finally, where flow velocities through the TCD intakes are high, head loss can be the dominant term and make it difficult or impossible to exclude overdraw using density blockage.

The cross-sectional areas and coefficients of the TCD intakes strongly influence their discharge capacities. As by closing a gate, reducing flow passage area through a TCD intake will reduce discharge through that intake for a particular differential pressure. If multiple intakes are in use, reducing the flow area of one intake will shift a portion of

the discharge to other intakes. If a single intake is in use, reducing flow area will increase head differential across the TCD. This is also true for, and can be used to evaluate, leakage. For a particular combination of open intakes and discharge, density-adjusted head differentials across the TCD can be computed and, with estimated leakage cross-sectional areas and coefficients, leakage discharges can be determined and the influence on release temperatures evaluated.

For a particular combination of open TCD intakes and discharge, a finite amount of energy is available to move water from the reservoir to the 815 intakes be it as an overdraw, an underdraw, or an intermediate-level withdrawal. When multiple TCD intakes are being used, the energy equation can be evaluated along each flowpath (from the reservoir to the 815 intakes through each of the operating TCD intakes) and the energy equations for each of these paths equated. The sum of the discharges through the TCD intakes can be set equal to the total power release. With definition of losses and intake coefficients which come from the physical model, the equations can be solved and the discharge distribution between intakes determined.

MATHEMATICAL MODEL STUDIES

The TCD can be thought of as an interface between the reservoir and the downstream river. Depending on how the TCD is operated and depending on the withdrawal characteristics of the TCD, specific withdrawals will be made from the reservoir. Depending on inflows and climatic influences, these withdrawals will reduce reservoir storage, reduce cold water reserves, and generally modify reservoir temperature, dissolved oxygen, and turbidity stratification patterns. The withdrawal characteristics of the TCD and the resulting withdrawal distribution as a function of how the TCD is operated is defined by the theory presented above and has been refined and confirmed by the physical model study. Thus, for alternative TCD's and for alternative TCD operations, the elevation and magnitude of release discharges can be defined. Computer or math models are the best available tools for evaluating TCD concepts and TCD operation influences on the reservoir. The math models were used to evaluate TCD effectiveness when operating with various reservoir elevations, with various hydrologic conditions, and with various climatic conditions. Historic reservoir, hydrologic, and climatic conditions for wet, dry, and typical years were used. Various TCD configurations (with alternative numbers of and elevations of gates) were evaluated with selected reservoir, hydrologic, and climatic conditions. The math model selected appropriate operating gates from the gates available to both meet downstream temperature objectives and to conserve cold water reserves within the reservoir. The math model in turn yielded predictions of resulting release temperatures and resulting stratified reservoir water quality conditions throughout the year of interest. Thus, the model output shows the potential effectiveness of various TCD designs, guides operation of the TCD to optimize release water quality (temperature) throughout the year, and allows determination of TCD effectiveness when operating under a broad variety of conditions.

A computer model of the river downstream of Shasta Dam was also implemented. The model considers initial release temperatures, hydrologic conditions, climatic conditions and river morphology, and predicts resulting river water temperatures at various stations. The model thus shows the warming and/or cooling that occurs as the water passes down the river. The implication of late summer warming is that typically, release temperatures from Shasta must be considerably colder than the desired water temperatures down river. Included in this model are the influences of Spring Creek Powerplant and tributary inflows on both discharge and temperature. The model thus allows consideration of alternative TCD operations and of alternative combinations of Shasta and Spring Creek releases. The model predicts release temperatures and release discharge magnitudes required from Shasta to meet downstream temperature objectives. As with the reservoir model, the river model has been thoroughly calibrated and verified using historic data.

When these two computer models are coupled with the predicted operating characteristics of the TCD, a complete picture and thus a complete analytical capability is achieved.

The reservoir and river computer models were used to sort through alternative TCD concepts and alternative design features. Typically, evaluations were made based on assumed reservoir conditions for 1989 (assumed during the winter of 1988-1989) and on historic reservoir conditions for 1988 (figure 5 - the third lowest water year of record since the dam was built), 1976 (the second lowest water year of record), 1977 (a critical low water year), and 1975 (figure 5 - one of the wettest years of record since the dam was built). Output from the computer models for these various runs is shown in the appendix of this report.

1988 - A fairly typical low water year and thus a good year to do comparative evaluations of TCD alternatives. Also, 1988 was a year of immediate interest for which a good database existed. Many alternatives were initially evaluated for 1988 and then, if they appeared worth pursuing, further evaluated for other years. TCD intake combinations studied were:

1) Use of the existing elevation 815 power intakes only - figure A1

2) 815, 738 (Historic operation - no TCD) - figure A2

3) 950, 920, 890, 860, 720 - Figure A3

4) 950, 815 - Figure A4

5) 970, 940, 910, 880, 750 - Figure A5

6) 970, 940, 910, 880, 720 - Figure A6

7) 970, 940, 910, 880, 650 - Figure A7

8) 970, 940, 910, 880, 815, 750 - Figure A8
1600 ft^3/s through 815 from April to August

9) 1000, 925, 815, 720 - Figure A9

10) 1000, 955, 925, 895, 815, 710 - Figure A10

11) 1020, 955, 925, 895, 815, 710 - Figure A11

12) 1045, 955, 925, 895, 815, 710 - Figure A12

13) 1000, 955, 895, 815, 710 - Figure A13

14) 970, 940, 910, 880, 815, 750 - Figure A14

15) 970, 940, 910, 880, 815, 750 - Figure A15
With modified Spring Creek releases

16) 1000, 900, 815, 710 - Figure A16

17) 1020, 900, 815, 710 - Figure A17

18) 1045, 900, 815, 710 - Figure A18

Test 8 was run simulating placement of the TCD over only three of the five units with peaking releases (represented as a continuous 1600 ft^3/s release from the 815 elevation from April through August) being passed through the two unaltered units. All other tests were run with withdrawals made from the same elevations for all five intakes.

Findings - The first run shows what would have resulted if all flow was released through the existing power intakes - note that the 56°F criteria is exceeded in the Shasta tailrace for nearly a 4-month period with a maximum temperature of 63.3°F occurring in September. As the flow passes down river (mixing with inflows and warming and cooling), the 56°F criteria is exceeded for 4 months with a maximum temperature of 62.2°F at Cottonwood Creek and for nearly 5 months with a maximum temperature of 64.2°F at Red Bluff.

Run 2 shows resulting release and river temperatures for historic operation using the low-level outlets to maintain reduced river temperatures. Note that the result is a delay of the maximum release temperature until October (when downstream warming is less of a problem); however, the 56°F criteria is still exceeded for nearly 4 months and the maximum release temperature is 64°F (0.7°F warmer than if all releases were made from the 815 level). Down river the 56°F criteria is exceeded for 4 months at Cottonwood Creek and for 5 months at Red Bluff; however, temperatures are reduced by 1 to 2°F at both Cottonwood Creek and Red Bluff.

Run 3 shows release and river temperatures that can be achieved when a multi-level intake is used. Note that maximum release temperatures are reduced by approximately 5°F and that the 56°F criteria is exceeded for approximately 2 months in the Shasta tailrace. Downstream maximum temperatures are reduced by 1 to 4°F from historic levels at both Cottonwood Creek and Red Bluff with 56°F significantly exceeded for 2 months at Cottonwood Creek and for 6 months at Red Bluff. This shows that if warm water is released early in the year and if the cold water is saved until later, substantial late summer river temperature reductions can be achieved. Thus, including a high-level intake in the TCD is very beneficial.

In run 4, all releases were made from the 950 level through June with releases made from the 815 level for the remainder of the year. This was done to evaluate the significance of a deep-level intake and to determine what could be achieved through the addition of a single high-level intake. Note that the 56°F criteria would be exceeded for approximately 1 month in May and June and for approximately 6 weeks in the fall. Maximum release temperatures would be approximately 59°F which is approximately the same maximum experienced with the multi-level intake (run 3). Likewise, except for the June peak river temperatures at Cottonwood Creek and Red Bluff, the river temperatures were comparable to those produced by the multi-level intake. It therefore appears that for years with reservoirs as high or higher than 1988, the addition of a high-level intake will achieve much of the temperature control required. The concern would be in critical low water years when the single high intake would have little or no use.

Runs 5, 6, and 7 compare multi-level intakes with bottom elevations of 750, 720, and 650. They show that very little cooling is gained by going to deeper bottom intakes (which reflects the small volumes of unaccessed cold water even for the 750 intake).

As was noted above, run 8 was made to evaluate what could be achieved by placing the TCD over only three of the five power intakes. The model was run to simulate base load releases through the TCD modified units and peaking releases through the unmodified units. Results showed performance that was similar to (although slightly poorer than) that achieved with a TCD over all five units. The concern with this option was that it allowed no operational flexibility and that performance would be lost when TCD modified units were down for maintenance.

Runs 9 through 18 compare alternative TCD gate placements. The indications are that little is gained (reduction of release and downstream temperatures) by raising the top intake from elevation 970 to elevation 1045. There may, however, be advantages in excluding overdraw. Likewise, increasing the number of intake levels from four to six shows little improvement in temperature control.

1989 - A theoretical water year which was assumed possible during the winter of 1988 - 1989. This assumed year represents a very low water year in which the reservoir peaked at approximately elevation 960 in March and dropped to approximately elevation 910 in September. TCD intake combinations studied included:

1) 950, 920, 890, 860, 720 - Figure A19

2) 970, 940, 910, 880, 750 - Figure A20

3) 970, 940, 910, 880, 720 - Figure A21

4) 970, 940, 910, 880, 650 - Figure A22

5) 970, 940, 910, 880, 750, 650 - Various forced distributions of release between the 750 and 650 intakes were studied to determine if extension of the TCD to the 650 level on only a portion of the intakes was possible; the distribution of release considered was:

750	650		
0%	100%	-	Figure A23
20%	80%	-	Figure A24
40%	60%	-	Figure A25
60%	40%	-	Figure A26
80%	20%	-	Figure A27
100%	0%	-	Figure A28

Findings - First note that for the hypothetical 1989 year with a TCD extending from elevation 950 to 720 (figure A19), the maximum release temperatures would not exceed 57°F and would only exceed 56°F for a 2- to 3-week period in October. River temperatures at Cottonwood Creek would exceed 56°F for approximately 7 months with temperatures being less than 57°F for the majority of the time and with a maximum of 59°F in October. River temperatures at Red Bluff would exceed 60°F for a 3- to 4-month period with a sustained maximum of approximately 60.6°F. Raising the top of the TCD to 970 (figure A20) had a negligible influence on performance.

Comparison of runs 20, 21, and 22 show that raising the bottom intake from 720 to 750 had little effect on summer release and river temperatures but did increase October release temperatures by over 2°F which resulted in river warming at Cottonwood Creek and Red Bluff of 1°F or less. Conversely lowering the bottom intake to elevation 650 yielded approximately a 2°F cooling of early fall release temperatures with a corresponding 1°F cooling of river temperatures at Cottonwood Creek and a slight cooling at Red Bluff. Thus, it appears that in very low water years (which this year represents), significant late season cooling can be achieved with deeper bottom intakes.

A point to notice is that it is fairly rare that the power plant would operate with four or five units simultaneously in September and October (even during peaking). Consequently, if it is considered desirable to extend the low-level intakes to a lower elevation (this may be difficult to do for several reasons), it may be adequate to do so with capacity for only two or three units. Runs 23 through 28 evaluate temperature reduction improvements that could be achieved with an intake with full discharge capacity at elevation 750 and with a lower (elevation 650) intake with reduced capacity. Comparison of figures A23 and A24 shows that a 650 intake with four unit capacity to be equally effective as a 650 intake with five unit capacity. Figure A25 shows that there is some, although not major, loss in performance if the 650 intake capacity is reduced to three units and additional loss (figure A26) if the intake capacity is reduced to two units. Additional reduction of capacity appears to yield major reductions in performance. Note that even with optimum cold water management (figure A22), in critical low water years, river temperatures at Cottonwood Creek will exceed 57°F for approximately a 1-month period and will exceed the 56°F standard over approximately a 7-month period.

1976 and 1977 - As this study progressed, it became evident that TCD performance should also be evaluated for extreme low water years or years with minimum cold water reserves. 1976 is the second lowest water year of record and represents a severe low water year for TCD design. 1977 was by far the lowest water year of record and represents a rare, critical condition. Reservoir water surface elevation over the 2 years is summarized in figure 5. The following alternative combinations of TCD intakes were evaluated for these 2 years:

1) Historical - 815 (no TCD) - Figures A29 and A38

2) 1045, 955, 925, 895, 815, 710 - Figures A30 and A39

3) 1020, 955, 925, 895, 815, 710 - Figures A31 and A40

4) 1000, 955, 925, 895, 815, 710 - Figures A32 and A41

5) 1000, 925, 815, 710 - Figures A33 and A42

6) 1045, 900, 815, 710 - Figures A34 and A43

7) 1020, 900, 815, 710 - Figures A35 and A44

8) 1000, 900, 815, 710 - Figures A36 and A45

9) 1000, 955, 895, 815, 710 - Figures A37 and A46

Findings - First note by comparing figures A29 and A30 that for 1976, use of the TCD will reduce July and August release temperatures by up to 10 to 12°F with resulting river temperature reductions of up to 6°F. However, by September, cold water reserves will be depleted and water temperatures delivered through the TCD will be comparable to historic releases. Runs 30 through 37 compare alternative TCD designs. The findings indicate little or no advantage to extend the top of the TCD from elevation 1000 to 1045 (as discussed later, the physical model shows that extension might be desirable to achieve overdraw control) or to increase the number of TCD withdrawal levels from four to six.

Comparison of figures A38 through A46 evaluate TCD performance for 1977, by far the lowest water year of record. The findings show that use of the TCD can reduce release temperatures by up to 16°F in June and July (corresponding cooling at Cottonwood Creek and Red Bluff would be 6 to 8°F) but that by August little cold water would be left in the lake and thus the potential for release cooling is minimal. It is possible that the TCD could be operated differently allowing more release warming in the early summer and conserve more cold water for cooling later in the season. As in 1976, the elevation of the top of the TCD (between 1000 and 1045) and the number of intake levels (four to six) has no effect on release and downstream temperatures. One point to note is that in very low water years the volume of cold water in Lake Shasta limits potential release and river cooling and even the best TCD will not be able to meet river temperature criteria. In years like 1977, with use of the TCD, maximum river temperatures at Cottonwood Creek and Red Bluff may approach or exceed 70°F and may exceed 65°F for up to a 2-month period.

1975 - A water year in which the reservoir peaked at approximately elevation 1070 in April and May and dropped to approximately elevation 1030 in September and 1005 in December. This represents a high water year. It was studied in particular to determine the need for total underdraw in the late summer and early fall. Comparison of the runs also show the cold water management significance of intermediate level intakes for a

high reservoir situation. The runs were made with the TCD on all five units and with the math model operated to optimize river temperatures. TCD alternative intake combinations studied were:

1045, 955, 925, 895, 815, 710 - Figure A47

1020, 955, 925, 895, 815, 710 - Figure A48

1000, 955, 925, 895, 815, 710 - Figure A49

1000, 955, 895, 815, 710 - Figure A50

1045, 900, 815, 710 - Figure A51

1020, 900, 815, 710 - Figure A52

1000, 900, 815, 710 - Figure A53

1000, 925, 815, 710 - Figure A54

Findings - Note that with the large cold water reserves, good control of downstream river temperatures is achievable. For all runs, river temperatures at Cottonwood Creek do not exceed 56°F and river temperatures at Red Bluff do not exceed 57°F. The objective of these runs was to determine the need for the entire late summer and early fall release to be from the low-level TCD intake in order to achieve acceptable river temperatures. This in turn dictates the need for absolute overdraw control (be it by extending the TCD above late summer maximum reservoir elevations or through use of gates and/or a closed top). The runs show that if the objective is to maintain 56°F water at Red Bluff, then no overdraw can be tolerated and absolute overdraw control must be maintained. However, if the objective is to maintain 56°F water at Cottonwood Creek, then some overdraw is acceptable and a smaller TCD (open top at elevation 1000 for example) is possible. Comparison of the runs shows that if releases are made from either the 1000 elevation or the 710 elevation (or a combination of the two elevations to meet intermediate temperature objectives), in August approximately 12 percent of the release could be from elevation 1000; in September no high-level withdrawal could be tolerated; and in October 15 percent of the release could be from the elevation 1000 intake. When the intermediate-level TCD intakes are also used, in August 21 percent of the release would be from the 895 level, 67 percent of the release would be from the 925 level, and 12 percent of the release would be from the 955 level. In September 17 percent of the release would be from the 895 level with the remainder from the 710 level. In October, 33 percent of the release would be from the 895 level, and 67 percent of the release would be from the 710 level. Thus, when the intermediate intakes are used, the cold water reserves are more optimally managed and total withdrawal through the low-level intakes is not required.

PHYSICAL MODEL STUDIES

A 1:72 scale physical model was used to study the alternative TCD concepts. Included in the model were all five penstock intakes (each individually valved to allow representation of any combination of operating units), a simplified representation of the trashrack structures, and a 1300- by 2000-ft area of reservoir topography surrounding the penstock intakes. The large area of reservoir topography and corresponding large reservoir volume were included in the model to at least partially eliminate boundary effects and simulate the very large prototype reservoir. To maintain a constant reservoir elevation during a test, water drawn from the reservoir and into the power intakes was recirculated and returned to the back of the model. When the model was operated with a temperature stratification, the recirculated water was generally not returned to the horizontal layer in the model reservoir from which it was drawn. Consequently, during a test, with time the temperature stratification profile in the model would become distorted. The time duration allowed for testing without recirculation-generated distortions was discharge dependent. Because of the large reservoir in the model, the time duration varied from 20 minutes to over an hour.

The 1:72 scale was selected primarily to allow inclusion of the large reservoir in the model. Based on the 1:72 scale, a discharge of 17,600 ft^3/s (the current discharge capacity of the powerplant) modeled as a discharge of 0.40 ft^3/s, the 490-ft maximum reservoir depth modeled as 6.80 ft, and the 15-ft penstock diameters modeled as 2.50 inches. At this scale, head loss associated with flow around structural members, vortex formation, and turbulent air entrainment all experience distorted scaling. These potential distortions were considered and compensated for as laboratory test results were interpreted.

The reservoir in the physical model was temperature, and therefore density, stratified. Stratification was achieved with refrigeration coils set in the lower back of the model (extending from the bottom of the reservoir to approximately elevation 850). The refrigeration coils maintained cold deep water while surface water was warmed by the ambient air. At times, in an effort to further strengthen the stratification, warm air was blown across the surface of the model reservoir and surface emersion heaters were used. Temperature stratifications as strong as those experienced in the reservoir in May were duplicated. As temperature gradients increased, vertical heat transfer in the model could not be overcome. Consequently, late summer stratifications could not be duplicated. Sufficient stratification was created to define temperature profile shifts across the TCD and how these profile shifts varied with operation, to evaluate the upper and lower bounds of generated withdrawal layers and determine structure configuration or topography influences, and to define density influences on the withdrawal characteristics of the TCD. Use of temperature-generated stratification (instead of saline-generated stratification) allowed quick turnaround between tests which in turn allowed considerably more tests to be run and gave more testing flexibility.

The head loss characteristics of the TCD intakes were found to be dependent on discharge and on intake size and configuration and independent of density influences. Consequently, intake losses could be evaluated with no stratification of the model reservoir. For these tests, testing duration was not limited by stratification distortions; therefore, back-to-back tests over extended periods were conducted.

Temperature profiles in both the model reservoir and between the TCD and the dam were monitored using columns of thermistors (figure 19) which were scanned by a data acquisition computer. Discharges were monitored using an ultrasonic flow meter that had been calibrated in the laboratory pipe stand. Head losses were measured using a high accuracy differential manometer. Upper and lower bounds of withdrawal layers were determined visually by observing displacements in vertical dye streaks.

Large Curtain TCD's

The physical model was used early in the study to evaluate the hydraulic performance of a large curtain TCD (figures 19 and 20). This curtain concept was representative of the large curtain proposed from the value engineering study. This concept was considered a likely alternative during the initial portions of this study. As shown in figure 19, the top of the curtain was at elevation 950 and the bottom of the curtain extended to the topography. Water could be drawn over the top of the curtain (overdraw - figure 10) around the entire perimeter. The curtain panel between the head tower (the remaining portion of a tower that was used to construct the dam) and the dam could be lowered to allow access to intermediate reservoir levels although it was never tested in this mode. Likewise, the bottom of the panel between the guyed support tower and the dam could be raised to allow access to the deepest water in the reservoir (underdraw - figure 21). The hydraulic performance of this curtain was evaluated both with the underdraw panel open and closed.

Most of the tests on the curtain were conducted with a water discharge of approximately 17,600 ft^3/s (maximum current powerplant discharge capacity). The curtain was tested with the underdraw panel both closed and open to various levels. The curtain was tested with reservoir temperature stratifications ranging from a mid-spring condition to a late spring or early summer condition. The model was tested with the reservoir water surface and thus the top of the warm surface layer ranging from elevation 952 (2 ft above the top of the curtain) to elevation 1039 (89 ft above the top of the curtain). For each case, the overdraw area was equal to the submergence times the curtain perimeter (approximately 1200 ft). Thus, flow conditions ranging from strong underdraw to strong overdraw were evaluated. Reservoir elevations, discharges, and underdraw areas tested are summarized in table 3.

Table 3. Shasta Curtain Model - Tests Conducted

Reservoir Water Surface Elevation	Temperature Range Surface to Bottom	Underdraw Open Area	Discharge
1039	65.0 - 43. 5°F	20,700 ft^2	17,850 ft^3/s
995	64.8 - 42. 9°F	2000 ft^2	17,500 ft^3/s
983	59.6 - 45.1°F	19,000 ft^2	12,600 ft^3/s
980	61.8 - 44.2°F	16,500 ft^2	17,400 ft^3/s
979	64.4 - 44.3°F	17,000 ft^2	17,200 ft^3/s
975	63.7 - 44.2°F	0 ft^2	17,600 ft^3/s
973	60.6 - 41.3°F	20,700 ft^2	18,100 ft^3/s
971	60.4 - 42.1°F	20,700 ft^2	17,600 ft^3/s
961	60.5 - 42.9°F	20,700 ft^2	17,600 ft^3/s
959	64.3 - 44.4°F	20,700 ft^2	17,500 ft^3/s
952	61.4 - 44.6°F	20,700 ft^2	17,500 ft^3/s

Intake cross-sectional areas (both for overdraw and underdraw) were selected to be sufficient to maintain intake velocities (at the curtain) at 1.0 ft/s or less. This was because of concerns with momentum or dynamic loading on the curtain. It was felt that the potential existed to generate dynamic or oscillatory response either in the curtain or in its support members that could yield either fatigue failure of the structure or excessive dynamic loading. One ft/s was arbitrarily selected as a maximum acceptable velocity after comparison of its corresponding velocity head or stagnation pressure with the potential density, head loss, and transient loads for which the curtain structure would be designed.

During each test, temperature profiles were periodically recorded at two stations in the reservoir and at one station between the curtain and the dam (figure 19). Since the reservoir was quiet with little vertical mixing, the profiles measured at the two reservoir stations were identical. As shown in figures 10 and 21, considerable three-dimensional mixing occurs between the curtain and the dam. As a result, strong vertical and lateral gradients or transitions occur between the curtain and the dam. Because of the profile variations inside the curtain, it is difficult to select a representative temperature profile inside the TCD to compare with the free reservoir (to determine density loads or to determine density-generated differentials that will influence withdrawal distribution). As shown on figure 19, temperature profiles inside the TCD were consistently measured at one arbitrarily selected station throughout the curtain studies. For each test, temperature profile data were collected and corresponding water densities computed. These densities were then integrated over each water column to define the density-influenced pressure fields on both sides of the curtain. These pressure fields and the shift between them yield both static loading on the curtain and the head differential required to generate the underdraw.

Typical temperature profiles generated are shown in figures 11, 12, 13, and 14. Figure 11 is an example of a temperature shift that would result if the reservoir is at elevation 975 and the curtain is operated with a predominant overdraw. The only underdraw occurs due to leakage with an estimated leakage cross-sectional area of 2000 ft^2. For the figure 11 test, the underdraw or leakage was determined to be 1900 ft^3/s and the corresponding overdraw was 15,700 ft^3/s. The observed flow patterns are illustrated in figure 10. Note that the strong overdraw fills the zone between the top of the curtain and the existing penstock intakes with warmer water. Leakage sustains cold water below the existing intakes. The 49.3°F observed withdrawal water temperature reflects a combined overdraw and leakage flow. When leakage influences are adjusted out of the observed withdrawal temperature, the mean overdraw temperature was found to be 49.9°F. This corresponds to the reservoir temperature at approximately elevation 937 (5 ft below the top of the curtain). This indicates the approximate centerline of the reservoir withdrawal layer (the reservoir water surface restricts the withdrawal layer and pushes the centerline below the elevation of the top of the curtain). Influences of this operation on temperatures below the penstock intakes are slight, showing that the overdraw is taken into the intakes and does not substantially mix below intake elevation. The overdraw is cooler than the thickened surface layer that has accumulated inside the TCD and thus, because it is more dense, it plunges down the inside of the curtain as a submerged water fall. The vertical drop varies with operating conditions but may be as much as 60 to 80 ft. As the flow drops, it encounters flow of its own density at which point a submerged hydraulic jump with substantial turbulence and vertical mixing results. If the leakage cross-sectional area would have been smaller, temperature shifts would have been even more pronounced.

Figure 12 shows temperature shifts that result when the curtain is operated with the reservoir at elevation 1039 (91 ft above the top of the curtain) and with simultaneous underdraw and overdraw (for this case, the resulting underdraw was 4036 ft^3/s and the corresponding overdraw was 13,814 ft^3/s). For this test, the underdraw cross section was approximately 20,700 ft^2 with some additional leakage. This flow path area is sufficient to pass the total release as an underdraw with velocities less than 1 ft/s. Overdraw flow patterns were basically the same as observed above (figure 10); however, a strong underdraw also occurs (figure 21). The underdraw generates a strong lateral and uphill current that also causes vertical mixing. Thus, reservoir temperature gradients between the top and the bottom of the curtain are weak and flow path cross sections, both over and under the curtain, are large. This corresponds to curtain operation early in the season (May or early June) with a high reservoir. Note that the resulting temperature shifts across the curtain are weak and that the head required to generate this flow, both due to losses and density effects, is small. Also note that the penstock withdrawal temperature, when adjusted for the underdraw, indicates that the mean overdraw temperature is 46.3°F which corresponds to the reservoir temperature at elevation 949 (1 ft above top of curtain). This indicates that the high reservoir does not restrict or force the upper withdrawal layer deeper. Also

observe that the temperature shift influences extend approximately 70 ft below the inverts of the power intakes (figure 12). This deeper extension of the temperature shift appears to be due to underdraw-generated vertical mixing.

Figure 13 shows temperature shifts that result when the curtain is operated with the reservoir at elevation 973 and with a 20,700 ft^2 underdraw cross section. In this case, the underdraw and overdraw are approximately equal (overdraw was 8940 ft^3/s and underdraw was 9160 ft^3/s). Submergence of the top of the curtain was approximately 31 ft with a moderate temperature differential between the bottom and top of the curtain. A moderate temperature shift results that extends over the full vertical height of the curtain. Both the reduced flow path areas and the stronger temperature gradients indicate that increased head differentials are required to generate the withdrawal flow. Also, density effects are significant enough to partially restrict overdraw and therefore increase the underdraw. Adjustment of the observed penstock withdrawal temperature indicates that the mean temperature of the overdraw is 48.4°F which corresponds to the reservoir temperature at the top of the curtain (which again indicates little surface influence on overdraw withdrawal layer distribution).

Figure 14 shows operation with a low reservoir (10 ft of submergence) and with a relatively strong temperature differential. With an underdraw flow area of 20,700 ft^2, the potential exists for significant overdraw and underdraw. However, density effects (the buoyancy of the warm surface water) are significant enough to greatly reduce overdraw. The observed overdraw was 3640 ft^3/s and the observed underdraw was 13,960 ft^3/s. Some of the overdraw was generated by entrainment or mixing of the underdraw with the warm water above it (inside the curtain). Adjustment of the observed penstock withdrawal temperature indicates that the mean overdraw temperature was 56.7°F, the reservoir temperature at elevation 935 (7 ft below the top of the particular curtain tested which shows surface influence). For this operation, observed temperature shifts and head differentials across the curtain are strong, although not as strong as with total overdraw.

Operating extremes, total underdraw and total overdraw, were also considered. For the large curtain concepts and for the range of discharges likely, it appears that if the reservoir is above the top of the curtain that at least some overdraw water will be entrained in the release and that total underdraw could not be achieved. The strength of the vertical mixing and the quantity of overdraw entrained is dependent on the cross-sectional area of the underdraw intake, the discharge (one to five units in use), and the influence of the temperature stratification. With a 20,000 ft^2 underdraw intake cross section, it appears that at a total discharge of 17,600 ft^3/s, 10 to 20 percent of the release (1760 to 3520 ft^3/s) will be overdraw, even in late summer with a strong temperature stratification. With one unit operation (total discharge of 3500 ft^3/s), the likely entrainment will be small, less than 5 percent. Once the top of the curtain is at the water surface, overdraw can be excluded except for leakage. To achieve a high

percentage underdraw with the reservoir water surface above the top of the curtain requires that head losses on the underdraw flow path be small. Thus, resulting shifts in the temperature profiles are also small. With the top of the curtain at the water surface, total underdraw can be maintained independent of discharge and head loss. However, to prevent excessive momentum loads on the curtain, the underdraw cross section should be maintained at 20,000 ft^2 or greater. With total underdraw, the cold inflow will fill the zone between the curtain and the dam to an elevation somewhat above the top of the intakes (approximately elevation 850). Temperature profiles above elevation 850 should be similar to reservoir temperatures. Since typically the greatest differences between temperature profiles occur in the upper portions of the profiles, resulting density differentials should be small.

Total overdraw, less leakage influences, can be achieved by dropping the bottom of the curtain to the bottom of the reservoir which forces all withdrawals to be made from over the top of the curtain. Although not evaluated in this study, losses over the top of the curtain will be dependent on submergence and thus on the available flow path cross section over the curtain. Again, because of the flexible structure, it is recommended that the overdraw cross section be maintained at 20,000 ft^2 or more. With a top perimeter of approximately 1200 ft, the corresponding minimum submergence (for total overdraw) would be 17 ft. By maintaining this submergence or more, head losses will also be held at acceptable levels. Temperature profile shifts that are generated by total overdraw are similar to profile shifts that are generated with combined overdraw and underdraw. Large differentials can be expected from the top of the curtain to below the penstock intakes (approximately elevation 800).

As testing progressed on the curtain concept, design also continued. Design loads were found to be larger than had been expected and consequently the cost of the large curtain concepts was considerably greater than what was first anticipated. As a result, numerous alternative TCD concepts were considered and, to a greater or lesser degree, evaluated. Concepts included smaller curtain structures, use of the diversion tunnel, modification of the river outlet works, excavation through the dam of a new penstock, and a steel selective withdrawal structure that would be placed over the existing penstock intakes and trashrack structure and attached to the dam face. Several of these options are discussed in more detail in the Concept C Summary Report (9). As a result of these studies, numerous uncertainties associated with the curtain concepts were identified. In particular, there were many uncertainties associated with the fabrication and installation of a large underwater curtain (3.0 to 5.5 acres of fabric depending on concept), its dynamic behavior, durability, and maintenance requirements. In order to answer some of these questions, a field test would be a requirement of the design process which would have added almost 4 years to the design stage. As a result, it was decided that the curtain concept would not be further pursued.

Rigid Selective Withdrawal Structure

The structure selected for final design was a rigid frame steel structure placed over all five existing intakes (figures 15 and 22). The structure is comprised of 50-ft-wide by 45-ft-deep vertical segments that would be prefabricated in the dry, floated into place, sunk into position, and attached to the dam. Because of topography, substantially deeper cold water reserves could not be accessed immediately below the existing penstock intakes. An extension was therefore added to the main body of the TCD to allow access to the 720 elevation. The extension is located between the main body of the TCD and the outlet works intakes (figure 15). The bottom of the extension was placed at elevation 720 (160 ft above the reservoir bottom) because of topography limitations, because the vertical face of the dam breaks to a 0.5:1 slope at the 720 elevation (it would be difficult to fit a structure well to this break), and because it was recognized that the withdrawal layer would extend well below the 720 elevation (see withdrawal layer theory discussed earlier in this report). Based on the previously discussed computer model studies, the top of the structure was positioned at elevation 1045 to allow positive late summer control of overdraw in all but extremely high water years. The structure would include gates set at various elevations to allow selection of the elevation of withdrawal. Vertical gates which control the 720 withdrawal were included at the tie between the extension and the main TCD body. Because the structure is rigid, higher intake velocities could be tolerated than with the curtain concepts. Intakes were therefore sized for a maximum intake velocity of 2.6 ft/s. Because of planned turbine upgrades, the structure was designed and tested for a maximum release discharge of 19,500 ft^3/s.

Although under normal operating conditions the TCD will be exposed to differential pressure loading resulting from wave loads and from flow-generated velocity heads, head losses, and density influences, it was found that the loading due to transient flow conditions (turbine start-up and load rejection) controlled much of the structural design. Numerous analyses were done to evaluate the influence on resulting transient loads of TCD size, spacing off of dam, top elevation, intake size, and possible use of a fixed top or cover. Use of a cover on the TCD was inviting because it would allow absolute control of overdraw even when the top of the TCD was submerged. Use of a cover would also allow the top of the structure to be lowered to elevation 1000 or lower without concern for associated overdraw problems. Unfortunately, covering the structure created an extended closed conduit which substantially increased transient loads. Thus, it was concluded that the top of the structure would be kept open.

Considerable effort was spent with the reservoir and river computer models to select a top elevation and confirm the 720 bottom elevation for the TCD (see previous section on math modeling). This work was conducted concurrently with the physical model study used to determine the hydraulic operating characteristics of the structure. As a result of the exchange between the two studies, a design was selected which included

adjustable gates or weirs which allowed the top face of the main structure to be set as low as elevation 1000 or as high as elevation 1045. This would allow overdraw, or at least partial overdraw, in the spring of all but the critical low water years (such as 1971). Two sets of intermediate gates were included in the structure, 1 set of 5 gates (1 gate in each 50-ft-wide section) was placed across the face of the main structure and extended from elevation 900 to elevation 945, and 1 set of 5 gates was placed across the face of the main structure and extended from elevation 800 to elevation 827 (directly in front of the existing penstock intakes - after completion of model testing, the top of the gate was lowered from 830 to 827 to reduce the weight of the gates). Because the TCD was not designed to withstand full hydrostatic load (with reservoir head on one side and a dewatered or partially dewatered chamber on the inside), pressure relief panels were included in the 800-827 gates to prevent structure collapse in case the structure was misoperated or in case of high transient-related surges.

Initial testing with the physical model concentrated on defining the discharge versus head differential (between the reservoir and the penstock intakes) characteristics of the alternative intakes. Each intake level of the structure (total overdraw at the 1045 level, total overdraw at the 1000 level, withdrawal through the 900 to 945 gates, withdrawal through the 800 to 830 gates, and total underdraw at the 720 level) was operated in the model with discharges ranging to 24,000 ft^3/s. The resulting differential pressures between the reservoir and the penstock intakes were measured and are summarized in figures 23, 24, 25, and 26. All tests, summarized in these figures, were conducted with no density stratification in the model. Consequently, differentials presented include no density compensations. For these tests, all gates at the level indicated were full open. Tests were run with withdrawal from all five units. Tests were run to determine the influence of simultaneous use of multiple levels of intakes on the observed differential discharge relationship. No influence was seen.

Figure 23 shows discharges generated by various differentials when operating with total overdraw at the 1045 level. Note that the discharge-differential relationships are dependent on submergence with greater submergences yielding reduced overtopping velocities and reduced differentials. At a discharge of 19,500 ft^3/s, observed differentials were 0.95 ft with a submergence of 25 ft (reservoir at elevation 1070), 1.23 ft with a submergence of 12 ft, and 1.65 ft with a submergence of 6 to 7.5 ft. At a discharge of 10,000 ft^3/s, observed differentials were 0.25 ft with a submergence of 25 ft, 0.37 ft with a submergence of 12 ft, and 0.44 ft with a submergence of 6 to 7.5 ft. Also note the cross-hatched zone on figure 23. This reflects a zone in which model observations indicated that air entrainment could be generated either from vortex formation or from the shear between the surface water and the plunging overdraw. Air entrainment is of concern in that it may yield either blowback, which could damage the TCD, or rough turbine operation. In either case, air entrainment is not desirable and consequently it is recommended that the structure not be operated in the cross-hatched range. The 1:72 model scale is too large to correctly represent air entrainment;

however, the model does show flow patterns that appear to have the potential to entrain air. These observations are to a degree confirmed by the literature which indicates that inception of air entrainment occurs at a plunging velocity of approximately 3.3 ft/s (10). This corresponds closely to overdraw velocities that result at the lower limits of the cross-hatched zone.

Observations at Flaming Gorge Dam, which has a somewhat similar TCD over its penstock intakes, show vortex formation with 30 ft or less of submergence above the top of the adjustable weir intake. These observations were not for flow over the top of the structure but for flow over lowered gates. The Flaming Gorge TCD has interlocking shutter gates, the top of which can be raised or lowered over a 90-ft range. These gates function much like the adjustable top gates proposed for the Shasta TCD in that as the season progresses the top of the shutter gates are lowered to maintain a desired overdraw. The Flaming Gorge experience might indicate that overdraw velocities be limited to 1.5 ft/s or less. For a 1045 overdraw at Shasta, this would indicate that the minimum acceptable submergence would be 38 ft (versus the 20-ft minimum submergence that the Shasta physical model shows) at a discharge of 19,500 ft^3/s. For the 1045 overdraw, use of the Flaming Gorge-based criteria appears to be conservative. Vortex formation and air entrainment are strongly dependent on the structure configuration and thus there is some question if observed vortex formation at Flaming Gorge necessarily means vortex formation with a 1045 overdraw at Shasta. However, because of scaling uncertainties, there is some question as to what constitutes adequate submergence. It is recommended that a final submergence criteria be established through direct observation of the actual structure. Because of peaking operations, criteria should be established based on maximum discharge. The criteria should likely require that a lower gate or gates be opened when submergence is less than a specified amount.

When overdraw is occurring over lowered upper shutters or when, with a low reservoir, the intermediate gates are being used in an overdraw mode, a more concentrated, higher velocity flow is generated. Consequently, the discharge generated by a specific differential decreases and the potential for vortex formation and air entrainment increases. Additional submergence is required to control air entrainment. Figure 24 shows the discharge-differential relationships predicted for this operation. Included are recommended minimum submergences based on model observations and the Flaming Gorge observations (this operation corresponds closely to the operation at Flaming Gorge and thus the Flaming Gorge submergence criteria may be fairly representative). Note in figure 24 the Flaming Gorge-based minimum submergence would require in excess of 60 ft of submergence to pass the maximum release of 19,500 ft^3/s. Model observations with their included scaling limitations indicate that the 19,500 ft^3/s could be passed with a submergence of approximately 30 ft. Note that maximum power discharge decreases with decreased net head and thus at lower reservoirs this submergence criteria is not as restrictive as it appears. As with the 1045 overdraw, it is

recommended that specific submergence criteria, with required opening of lower gates, be established through observation of actual structure performance. The model and Flaming Gorge-based criteria give an indication of the probable final criteria.

Figure 25 shows the observed discharge-differential relationships for the intermediate gates and the 720 or low-level gates in the Shasta TCD. Included are the gates at the 900 to 945 level and the gates at the 800 to 830 level in the final TCD model configuration. Also included (as dashed lines) are other intermediate gate configurations that were considered during concept development. Note that head losses through the low-level (720) gates are substantially larger than losses that occur due to flow through the intermediate gates. Underdraw losses are of similar magnitude or somewhat larger than losses generated in overdraw with the larger submergences. Losses through the intermediate gates are smaller with losses through the 800 to 830 gates being approximately 0.28 ft at the maximum discharge of 19,500 ft^3/s. Note again that as with overdraw, differentials increase as a power function of discharge. Consequently, relatively small discharges of a few thousand cubic feet per second can be passed on any flow path with very little differential.

Note also that the bottom line on figure 25 shows differentials required to generate simultaneous, multiple level withdrawals (in this case, simultaneous withdrawals were made at the 800-830 and 880-970 levels). The bottom curve illustrates the additive nature of the discharge characteristics. A net differential pressure between the reservoir and the penstock intakes imposes a differential on any available flow path through the TCD. As previously discussed, this differential satisfies velocity head, head loss, and density compensating demands. If there is no density stratification (as was the case in the head loss evaluation tests), discharges generated by a common differential can be added to determine the total discharge when multiple levels of gates are in use. For example, note that the maximum discharge of 19,500 ft^3/s was passed with a differential of approximately 0.075 ft. Note that with this differential, a discharge of approximately 9750 ft^3/s could be passed through the 800 to 830 level gates operating by themselves or a discharge of approximately 9750 ft^3/s could be passed through the 880 to 970 level gates operating by themselves. With both levels of gates open, the observed discharge equals the sum of the individual discharges. As noted in the theory section of this report, when density stratification exists, density compensations on net differential must be made to compute resulting discharges. An example calculation where density compensations are included follows later in this report.

Figure 26 shows the results of efforts to increase discharge as a function of differential on the low level (720) or underdraw flow path. The initial TCD concept included a sharp-edged intake at the 720 level, the face of the TCD positioned 40 ft off of the dam, and a 100-ft vertical tie between the main body of the TCD and the extension (a gross cross sectional area at the tie of approximately 4000 ft^2). The top curve on figure 26

shows measured differential as a function of discharge on the underdraw flow path for the initial structure. Note that at a discharge of 19,500 ft^3/s, a differential of approximately 2.05 ft was observed. The bottom curve in figure 26 shows measured differentials across the 720 intake (from reservoir to middle of extension) for the initial concept. Note that at a discharge of 19,500 ft^3/s, a differential of 0.5 ft (approximately 25 percent) of the total differential on the flow path) results. The high differentials required to generate the underdraw was of concern in that at high discharges it becomes a dominant term which makes it impossible to exclude overdraw if the reservoir is above the top of the structure. The associated head losses also are large enough that lost power is of concern.

Four modifications were considered which had potential to reduce the underdraw differentials or increase underdraw discharges. The face of the TCD was moved from 40 to 45 ft off of the dam. This was done primarily to reduce transient loads with a secondary effect of reducing differentials required to generate an underdraw. In addition, a bell-shaped intake was placed on the bottom of the extension at the 720 level (figure 27), guide vanes were inserted in the extension in an effort to improve approach flow conditions to the tie between the main body and the extension (figure 27), and the vertical dimension of the tie between the extension and the main body was increased to 130 ft (creates a gross cross-sectional area at the tie of approximately 5850 ft^2. Evaluation of these modifications showed that differentials across the 720 intake were the same either with or without the bell. Consequently, the bell offered no improvement and could be left out of the design. Likewise, the internal guide vanes did not significantly reduce required differentials or increase underdraw discharges at fixed differentials. Therefore, the guide vanes could likewise be left out of the design. Increasing the cross section of the tie (from 4000 ft^2 to 5850 ft^2) substantially reduced required differentials or increased underdraw flow rates resulting in a required reservoir to penstock intake differential of 1.36 ft at the maximum discharge of 19,500 ft^3/s. This compares to the 2.05 ft required in the initial design. The final TCD (figures 28 and 29) concept generally reduces required underdraw differentials by about one-third.

Testing then continued with a temperature-stratified model reservoir. As was previously noted, numerous theories are available which predict the upper and lower bounds of withdrawal layers. These theories were typically developed using simplified intake and reservoir geometries. There was a question as to what theory would best apply to the Shasta TCD and whether the intake geometry (in particular for the downward-facing 720 intakes) and reservoir topography would distort the resulting withdrawal layer. Of greatest concern was the withdrawal layer generated by an underdraw or 720 withdrawal. The model was used to select a theory or adjusted theory that would agree with observed withdrawal layer bounds. It was also used to determine the lower limits of the withdrawal and, in particular, determine the volume of water that could not be accessed with the proposed TCD design (because the 720

intake is approximately 160 ft above the bottom). Numerous tests were run with various discharges and with various strengths of temperature and density gradients through the lower withdrawal layer zone. Dye was dropped vertically through the withdrawal zone approximately 430 ft upstream from the TCD structure. Bohan and Grace (5) found that for orifices, contraction distortions (the flow contracting into the intake) occur in the first three orifice diameters (approximately 150 ft) downstream of the intake, and for overflow weirs the contraction occurs in a distance equal to the withdrawal layer thickness (125 to 300 ft depending on discharge and temperature gradient). Thus, the withdrawal layer thickness was observed at a sufficient distance from the intake to assure no local contraction effects. Distortion of the vertical dye streak by the withdrawal flow was observed and referenced to a vertical scale at the initial dye injection point. In this way, the upper and lower bounds of the withdrawal layer were determined. It was found that the equation of Smith et al. (6) generally predicted the withdrawal layer bounds but that it tended to over predict withdrawal layer thickness by approximately 20 percent on the average with withdrawals from weaker stratifications being more accurately predicted (within 2 to 4 percent) and withdrawals from stronger temperature stratifications being less accurately predicted (over predictions of withdrawal layer thickness of up to 41 percent were noted) .

Based on a computer prediction of the reservoir temperature profile for September 1988, withdrawal layers (as a function of discharge) generated by a 720 withdrawal were computed. The reservoir temperature profile used was generated through progressive releases from the 955, 925, 895, 815, and 720 levels through the year. The release elevation was selected based on desired river temperatures. The profile includes a strong gradient through the 720 elevation.

This strong gradient limits or minimizes the resulting withdrawal layer thickness. It therefore yields the largest volume of water below the withdrawal layer that could not be accessed with a 720 withdrawal. Withdrawal layer bounds or limits were predicted using the Smith et al. equation. Predicted withdrawal layer thicknesses were reduced by 20 percent as was indicated by physical model observations. The predicted withdrawal layer bounds, corresponding withdrawal discharges, and volumes of unaccessed deeper water are shown on figure 30. Of particular concern is the volume of unaccessed water or the volume of cold water that could not be released in late summer. Note that this varies from 27,000 acre-ft at a discharge of 4000 ft^3/s, 7200 acre-ft at a withdrawal discharge of 19,500 ft^3/s. Note also that a shear exists between the withdrawal layer and the residual water below. This, in conjunction with the mixing influences of the peaking operation, should mix and gradually entrain deeper water into the withdrawal. Thus, it is expected that the volume of unaffected cold water in the reservoir will be small.

Also of interest with a stratified reservoir were temperature profiles that result inside the TCD with various operations. The TCD was operated with a combined 1045 overdraw

and 720 underdraw. The observed internal temperature profile and the corresponding reservoir profiles are shown on figure 16. Note that temperatures in the upper portion of the TCD correspond to mean temperatures in the upper withdrawal layer and that the upper portion of the TCD functions as a conduit transporting the withdrawal water vertically down to the intake. In the zone of the penstock intakes (800-830), mixing occurs between the underdraw and overdraw and a strong transition or gradient results. Below this mixing zone (below approximately elevation 780), the influences of the underdraw can be observed. Basically, this shows the upward transport of the deep cold water. Since, in this case, the deep water was about the same temperature as the reservoir water between elevation 720 and 815, shifts in the temperature profile were small. Figure 16 also shows temperature profile shifts that would result if the TCD were operated solely in either underdraw or overdraw. Except for the mixing that occurs at the penstock intake, the profiles observed above and below the penstock intakes are basically independent and representative of profile shifts that would result solely as a function of underdraw or overdraw.

Two additional runs were made to evaluate exclusion of overdraw when the top of the structure is submerged. The first run, shown in figure 17, was made with the top of the TCD at elevation 1020, with the reservoir water surface at elevation 1038, and with the underdraw or 720 control gates open. Thus, there were two potential withdrawal flow paths (720 underdraw and 1020 overdraw). The test began at a small discharge. At small discharges, the buoyancy of the warm surface water coupled with the small underdraw differentials excluded any overdraw. Thus, at small discharges, the entire withdrawal was from the 720 level. In the test, discharges were progressively increased until significant overdraw was observed. The reservoir and internal temperature profiles observed at this inception point are shown in figure 17. Evaluation indicated that for this condition the overdraw discharge was 1050 ft^3/s and the underdraw discharge was 4380 ft^3/s. It is expected that with stronger reservoir temperature profiles and warmer surface water, additional buoyancy would exclude overdraw and allow increased underdraw (possibly up to 8000 to 10,000 ft^3/s) without overdraw. Note the parallels between the observed temperature profile shifts and the profile shifts shown in figure 16. The profile shift in the upper portion of the TCD was less pronounced. It is thought that this is due to the relatively small overdraw discharge and its limited flushing action inside the upper portion of the TCD.

As a comparison, the TCD was run with the top of the TCD at elevation 1020 with the reservoir water surface at elevation 1028 and with both the 800 to 830 gates open and the 720 (or underdraw) control gates open. Again, testing started with small total releases. Discharges were increased until inception of overdraw occurred. The profiles shown on figure 18 were those observed at the inception point. As is noted, the observed overdraw discharge was approximately 200 ft^3/s, the discharge through the 800 to 830 gates was approximately 7600 ft^3/s, and the underdraw discharge was approximately 2800 ft^3/s. Thus, the total release was approximately 10,600 ft^3/s. Note

that by opening the 800 to 830 gates, resulting differential pressures were greatly reduced which allowed much greater total release discharges prior to inception of overdraw. It is expected that with stronger reservoir temperature profiles and warmer surface temperatures, the surface water would have greater buoyancy and thus with the 800 to 830 gates and the 720 gates full open, 19,500 ft^3/s could be passed with no overdraw. Again, the temperature profile shifts in the upper portion of the TCD indicate a weak overdraw; that is, the full potential of the shift (as indicated in figure 18) is not developed. It is expected that with an increased overdraw discharge, temperatures in the upper portion of the TCD would approach 58° to 59°F.

Example Computation of TCD Performance with Simultaneous Multi-Level Withdrawal

Using the final TCD concept (figures 28 and 29), the reservoir temperature profile given below (developed from the math model for August of 1975), and the hypothetical operation with the top gates in the lowered position (top at elevation 1000) and all other gates open (900-945, 800-830, 720), what will be the distribution of withdrawal between the gate levels and what will be the resulting temperature of the combined release? It is recognized that the above gate operation is not realistic but it best shows all computational techniques required. To develop performance curves, assume a series of penstock intake to reservoir differentials and compute the resulting flow rates. Adjust the differentials for temperature profile shifts. Determine discharges and average water temperatures through each level of gates. Sum discharges to determine the total release and compute a weighted average temperature based on the discharge distribution.

Observations and the literature indicate that the withdrawal characteristics of each level of intake will be as follows:

For the elevation 1000 overdraw, the maximum velocity in the withdrawal layer will be above elevation 1000 but because the upper bound of the withdrawal layer is limited by the water surface, the withdrawal layer likely will extend deeper below elevation 1000 than it extends above. Indications are that the reservoir temperature at elevation 1000 (the weir elevation) will be representative of the mean withdrawal temperature.

For the 900 to 945 and 800 to 830 gates, the mean withdrawal temperature will closely correspond to the reservoir temperature at the elevation of the gate centerline.

For the 720 withdrawal, the mean withdrawal temperature approximately equals the reservoir temperature at elevation 700.

So for this example, the mean temperatures of the various withdrawals are:

1000 overdraw - 73.5°F, 900 to 945 (922.4 centerline) - 56.5°F, 800 to 830 (815 centerline) - 46.5°F, 720 underdraw - 45.2°F.

Table 4. Reservoir Profile

Elevation	Mean Temperature (°F)	Relative Density	Differential Head
1035			
	78.5	.99685	14.9528
1020			
	76.5	.99714	19.9428
1000			
	72.0	.99775	19.9550
980			
	67.0	.998342	19.9668
960			
	62.5	.998810	19.9762
940			
	58.0	.999206	19.9841
920			
	53.0	.999558	19.9912
900			
	47.0	.999860	19.9972
880			
	45.7	.999902	19.9980
860			
	45.6	.999904	19.9981
840			
	45.5	.999907	19.9981
820			
	45.5	.999907	19.9981
800			
	45.4	.999909	19.9982
780			
	45.4	.999909	19.9982
760			
	45.3	.999912	19.9982
740			
	45.3	.999912	19.9982
720			
	45.2	0999915	19.9983
700			

Because there are two intakes feeding the TCD from above the penstock intakes, an estimate of the withdrawal distribution between the two is required to compute temperature, and thus density corrections, to the differentials. Later in the computation, the assumed distribution will be checked and corrected if needed. Noting that both relatively high differentials are required to generate an elevation 1000 overdraw with 35 ft of submergence (figure 24) and noting the warm water temperatures that will cause buoyant exclusion, it could be assumed that overdraw discharges will be small. Based on the model-observed temperature profiles with small overdraws (figures 17 and 18), it appears that weaker flushing of the upper part of the TCD occurs and, as a result, water temperatures inside the TCD between elevations 1000 and 922.5 will be approximately 69.5°F (cooler than the 73.5°F that would occur with a strong overdraw and approximately equal to the reservoir temperature at elevation 980 - 20 ft below the weir elevation). At 69.5°F, relative density equals 0.99805. With this temperature between elevations 1000 and 922.5, the head inside the TCD over this vertical range is (1000 - 922.5) (0.99805) = 77.3489 ft of water. The reservoir head between these elevations (integrated from the reservoir profile in table 4) is 77.3841 ft. So temperature, and thus density effects, alone will generate (77.3841 - 77.3489) or 0.0352 ft of buoyant exclusion to the 922.5 level. Assuming that the bulk of the high-level withdrawals will be from the 900 to 945 gates, the water temperatures inside the TCD will be slightly warmer than 56.5°F (the reservoir temperature at elevation 922.5). If the temperature in this reach is 57.0°F (indicates that 96 percent of the upper level flows are from the 900 to 945 gates), the head over the vertical reach inside the TCD is (922.5 - 815) (relative density of 57.0 water) = 107.4230 ft. The reservoir head over this range is 107.4802 ft. The temperature-generated differential would thus be (107.4802 - 107.4230) = 0.0572 ft. So total generated adjustments to the differential for the elevation 1000 overdraw would be (0.0352 + 0.0572) or 0.0924 ft.

For a first flow distribution calculation, assume that the differential between the penstock intakes and the reservoir is 0.095 ft (enough to generate a slight overdraw at elevation 1000). The density-corrected differential for overdraw is 0.095 - 0.092410 = 0.002590 ft. The corresponding overdraw discharge with a submergence of 35 ft is approximately 300 ft^3/s (figure 24). The density corrected differential for the 900-945 withdrawal is 0.095 - 0.057140 = 0.037860 ft. The corresponding withdrawal discharge through the 900-945 gates is approximately 5200 ft^3/s (figure 25). This is approximately 94 percent of the upper level withdrawal which indicates that the 96 percent assumption is fairly close. There is no vertical displacement and thus no density adjustment for the 800-830 withdrawal. Thus, for the available differential of 0.095 ft, the corresponding discharge through the 800 to 830 gates is approximately 11,300 ft^3/s (figure 25). Finally, for the 720 underdraw, the density adjustment to the differential between elevations 720 and 815 would be (815 - 720) (relative density of 45.2 water) less the reservoir head over this range. This equals [(95)(.999915) - 94.991445] or 0.000480 ft. Thus, the density-adjusted differential for the 720 withdrawal is 0.095 - 0.000480 = 0.09452 ft. The corresponding 720 withdrawal is approximately 4600 ft^3/s (figure 25). The total release generated by the 0.095 ft differential is 300 + 5200 + 11,300 + 4600 = 21,400 ft^3/s. Thus, the 0.095-ft differential will generate a withdrawal greater than the expected maximum

discharge of 19,500 ft^3/s when all gates are open. The mean temperature of the release would be [(300)(69.5)+(5200)(56.5)+(11,300)(46.5)+(4600)(45.2)]/21,400 which equals 49.0°F.

Similarly, differentials other than 0.095 ft can be evaluated. If the differential was 0.065 ft, the differential when density adjusted would not be sufficient to generate elevation 1000 overdraw. Thus, the internal water temperature between elevations 922.5 and 815 would be 56.5°F (the reservoir temperature at elevation 922.5). The resulting density correction between elevations 815 and 922.5 would be (107.5)(0.999322) - 107.48017 = 0.053055 ft. The corresponding adjusted differential and discharge would be (0.065 - 0.053055) or 0.011945 ft and 1800 ft^3/s (figure 25). Again, there is no density adjustment to the 0.065 differential for the 800 to 830 gates (because there is no vertical displacement from the penstock intakes). For a 0.065-ft differential, the corresponding discharge through the 800 to 830 gates is 9200 (figure 25). For the 720 withdrawal, the density-adjusted differential would be (0.065 - 0.00048) = 0.06452 ft. The corresponding discharge would be approximately 3500 ft^3/s (figure 25). Thus, a 0.065-ft differential would generate a total withdrawal of 14,500 ft^3/s with an average temperature of 47.4°F.

With a differential of 0.053 ft, there would be little or no withdrawal from the elevation 1000 and 900-945 gates (due to density influences). The discharge through the 800-830 gates would be approximately 8000 ft^3/s and the discharge at the 720 level would be approximately 2900 ft^3/s. Thus, the total release would be 10,900 ft^3/s with a mean temperature of 46.2°F.

With a differential of 0.030 ft, there would be no flow from either the 1000 or 900 to 945 gates. The withdrawal through the 800-830 gates would be approximately 5200 ft^3/s and at the 720 level would be approximately 2000 ft^3/s. Thus, the total release would be 7200 ft^3/s with a mean temperature of 46.1°F. Of course, with no differential there would be no withdrawal.

The findings of the above analysis are summarized in figures 31 and 32. Note that the withdrawal distribution and resulting mean temperature are dependent on the total discharge. Thus, with a particular combination of open gates, as the plant goes through its normal peaking cycles the mean release temperature will change. Note also that the relationship shown in figure 32 (release temperatures warming with increased discharge) is very dependent on the gates in use. It is possible with only the 800 to 830 and 720 intakes open that release temperatures at higher discharges will be colder. It should be noted that these performance characteristics exist, that gates should be set for worst-case operations, that approximate performance can be computationally evaluated as was done in this example problem, and that confirmation and refinement can be achieved through monitoring prototype performance.

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5. Bohan, J.P., and J.L. Grace, *Mechanics of Flow from Stratified Reservoirs with Interest of Water Quality; Hydraulic Laboratory Investigations*, Technical Report H-73-4, U.S. Army Engineers Waterways Experiment Station, 1969.
6. Smith, D.R., S.C. Wilhelms, J.P. Holland, and J.R. David, *Improved Description of Selective Withdrawal Through Point Sinks*, Draft Technical Report, U.S. Army Engineers Waterways Experiment Station, 1985.
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9. LaFond, R.W., *Concept C Decision Memorandum - Shasta TCD*, Bureau of Reclamation, June 20, 1989.
10. Ervine, D.A., E.J. McKeogh, and E.M. Elsway, "Effect of Turbulence Intensity on the Rate of Air Entrainment by Plunging Water Jets," *Proceedings of the I.C.E*, part 2, vol. 69, pp. 425-445, June 1980.

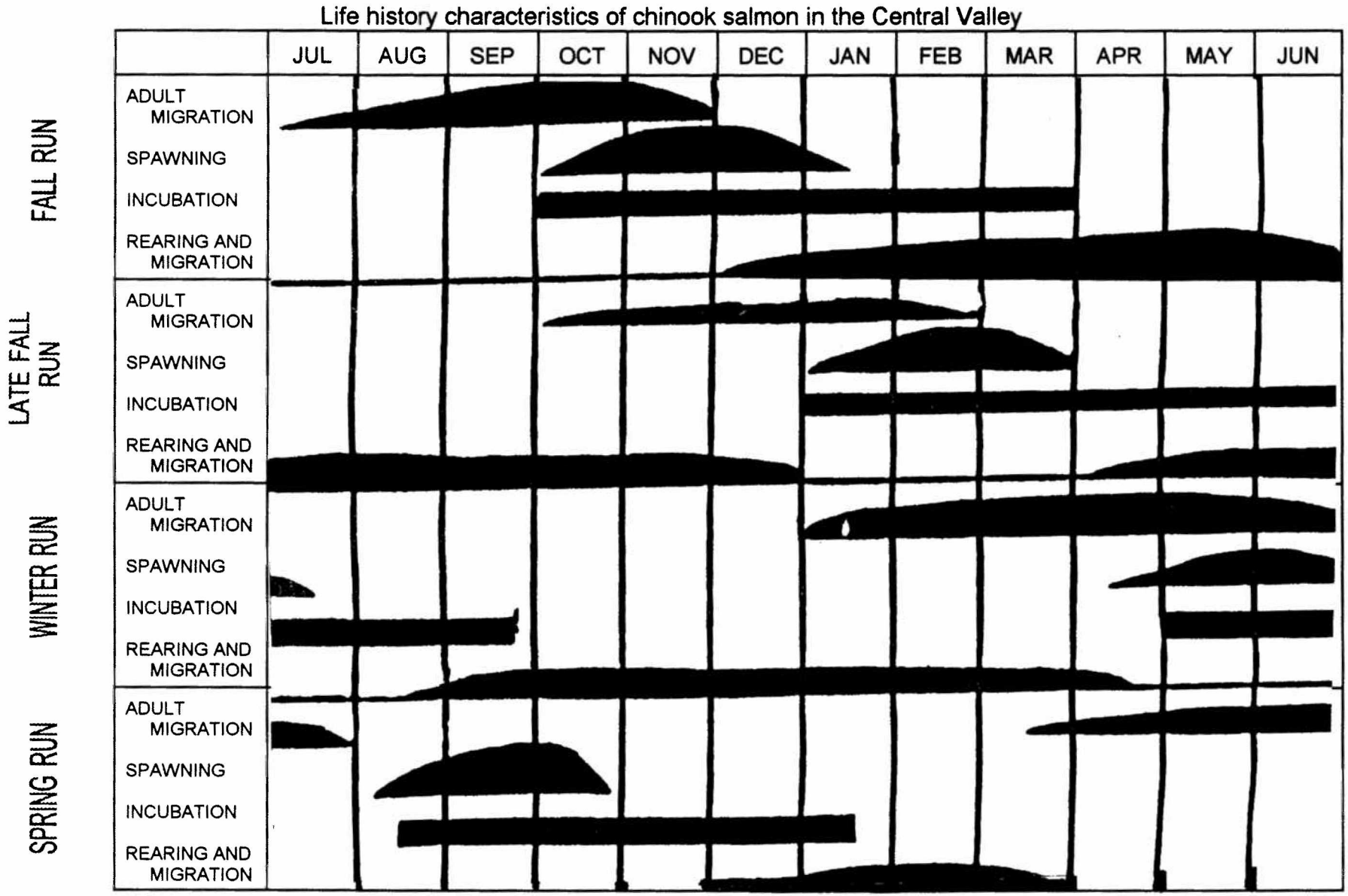


Figure 1. Timing and duration of salmon runs in the Sacramento River.

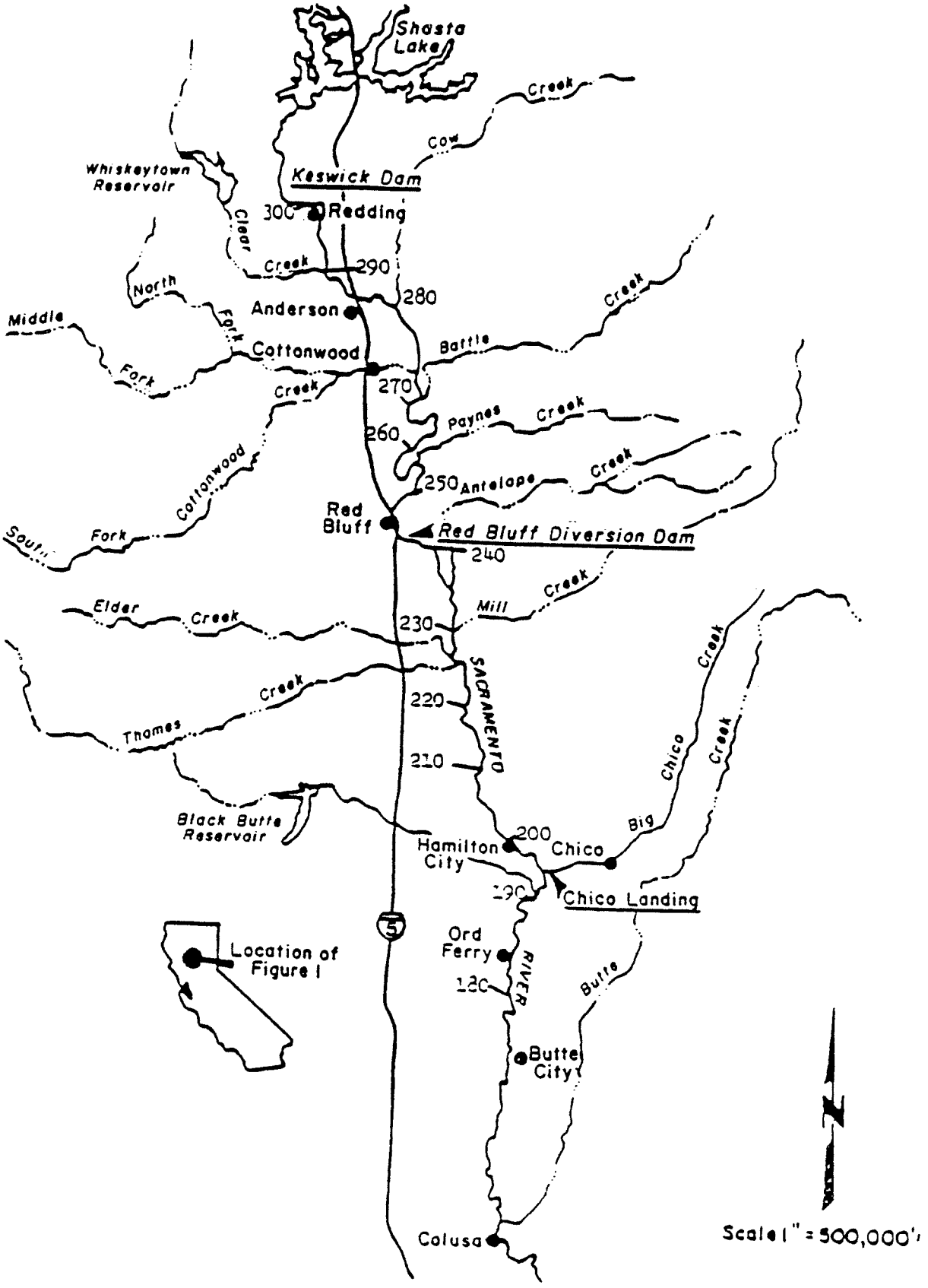


Figure 2. Location map showing the study reach between Keswick Dam and Ord Ferry in Northern California.

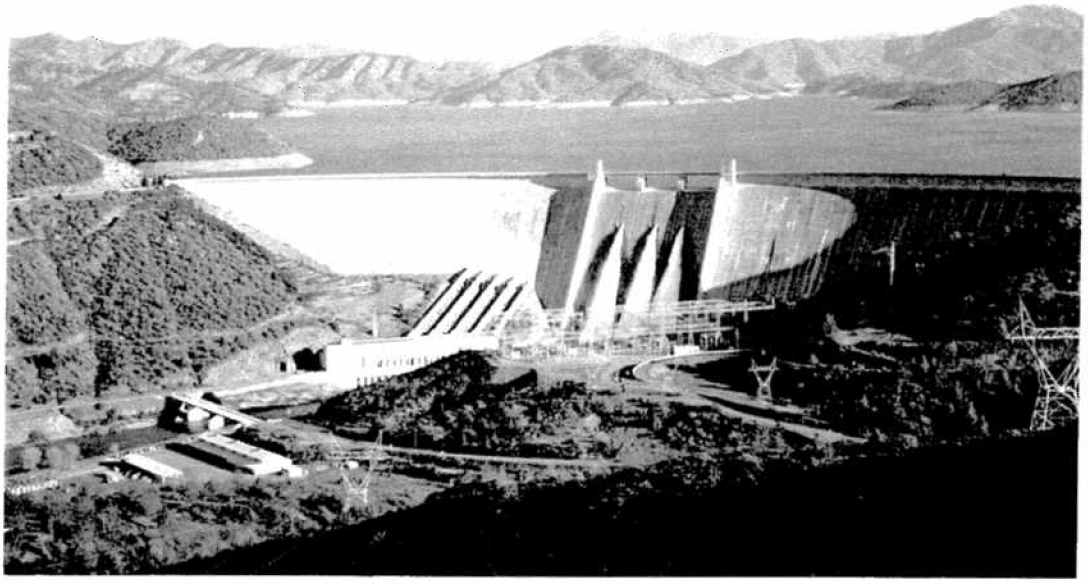


Figure 3. Shasta Dam with mid-level outlets operating.

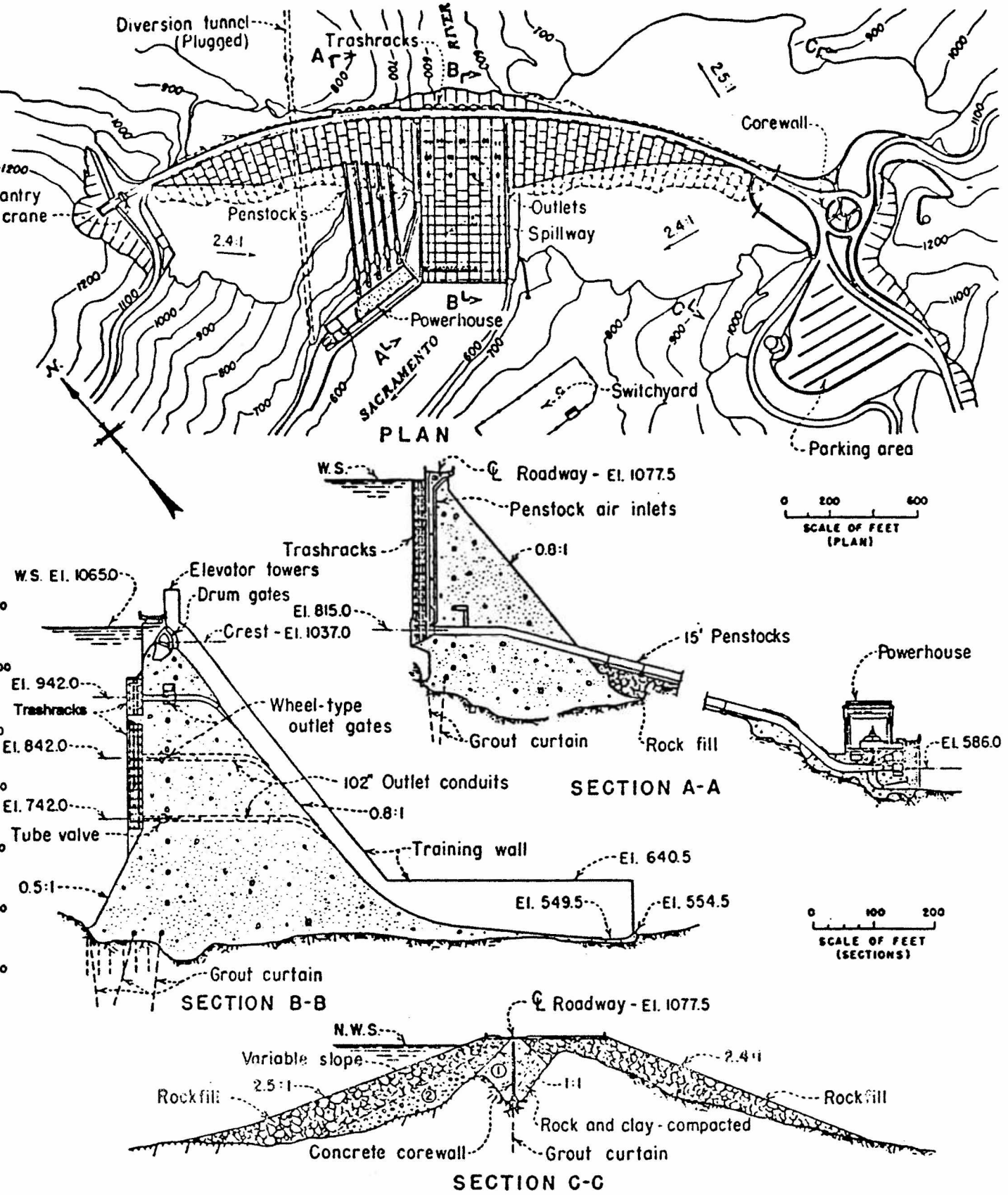


Figure 4. Shasta Dam - plan and sections.

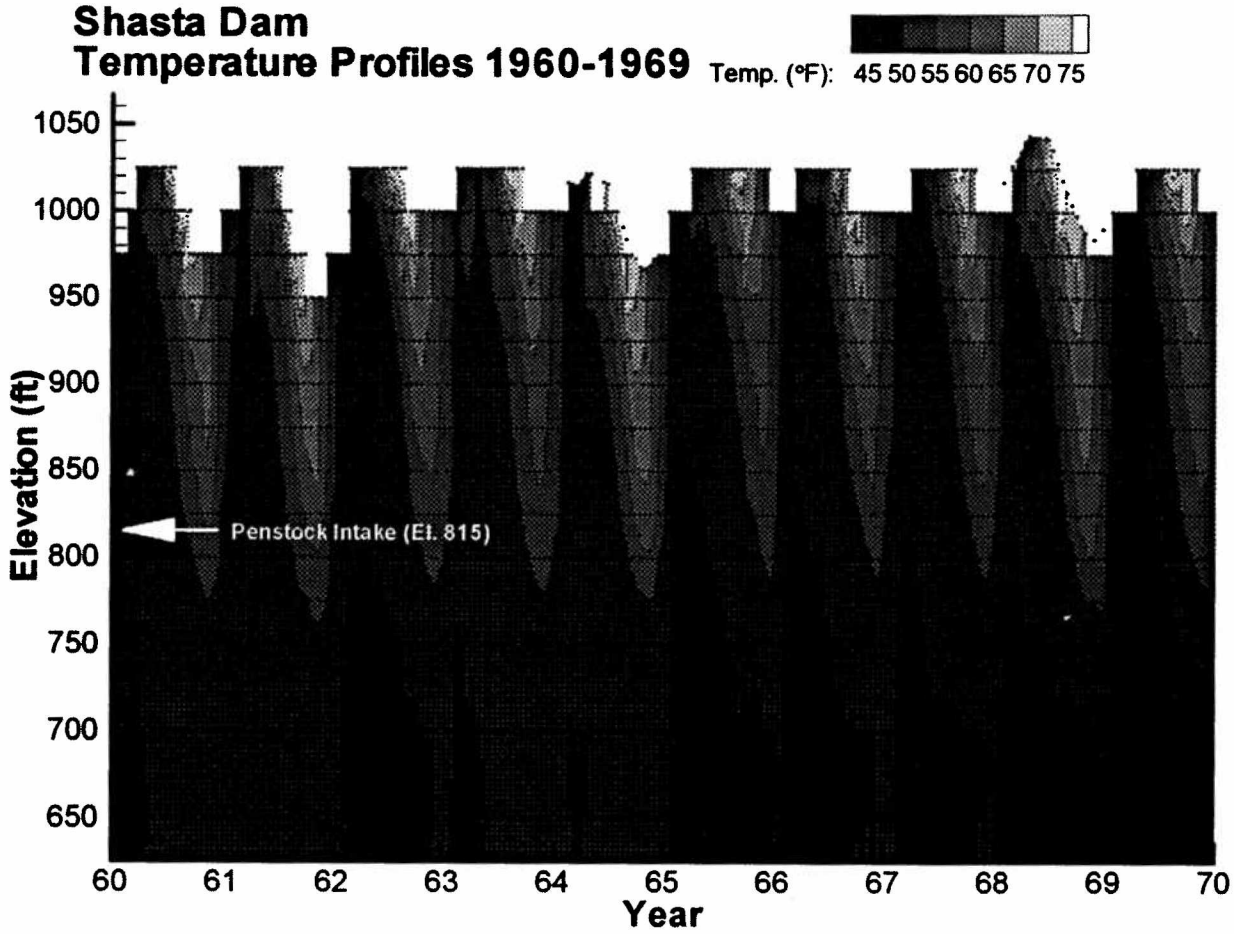


Figure 5. This plot illustrates the variations in water surface elevations and reservoir stratification in the Shasta Dam forebay for the years 1960 through 1969. The black dots represent actual temperature measurements.

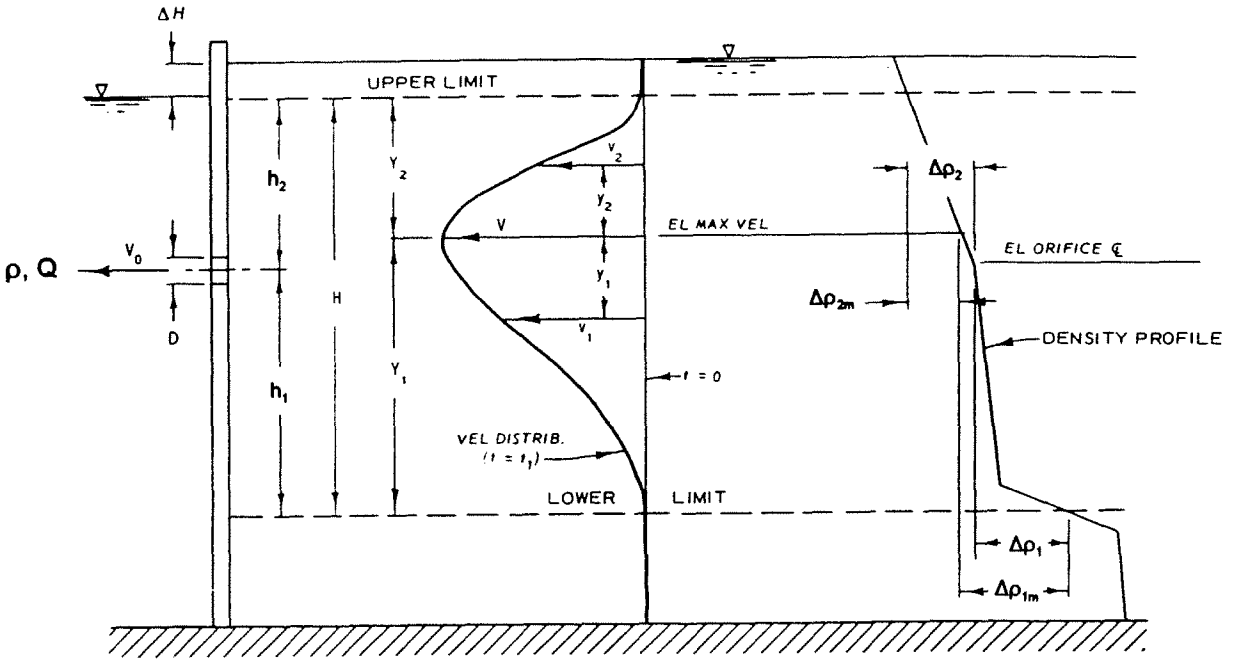


Figure 6. Definition sketch of variables for orifice flow.

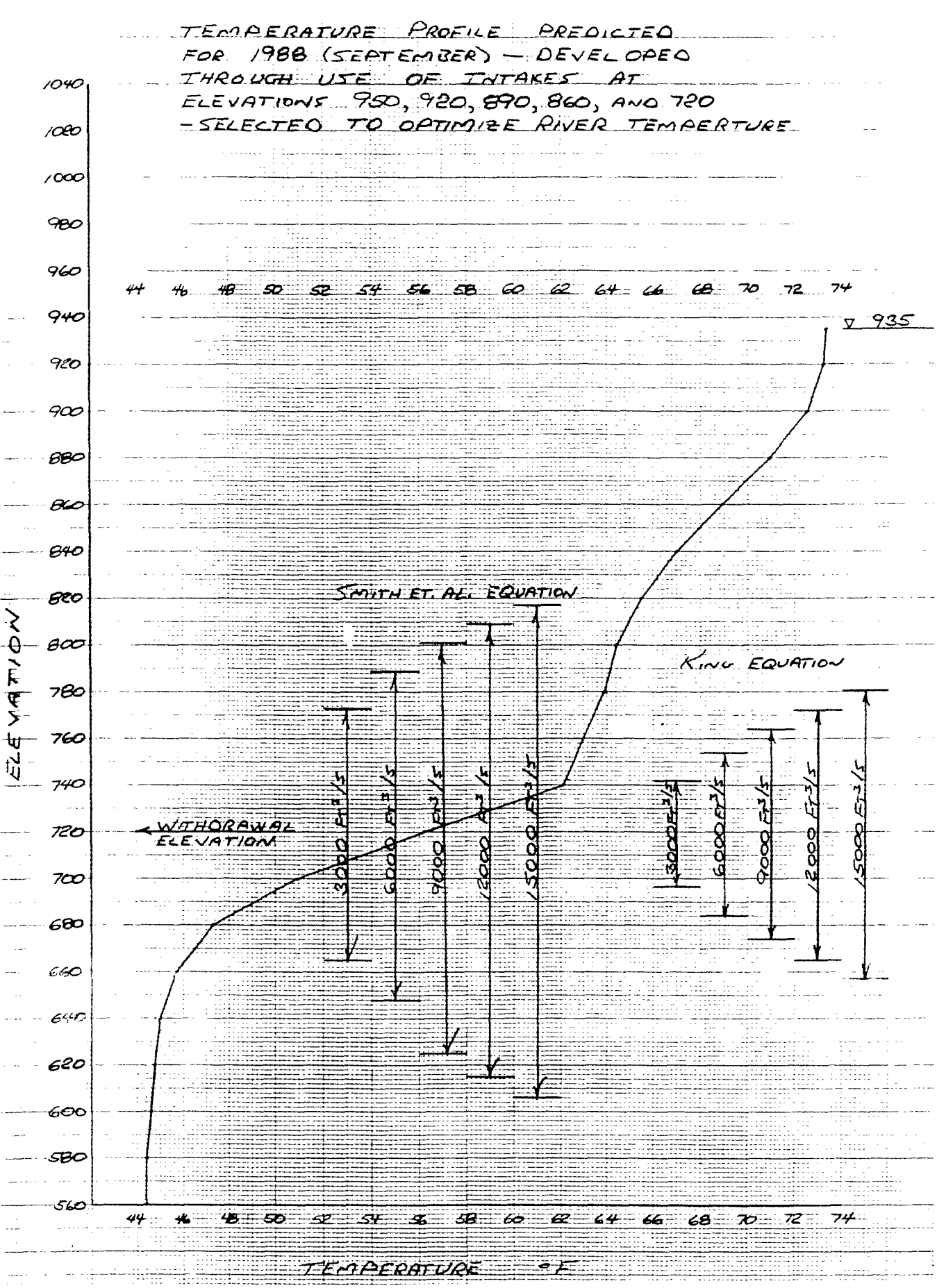


Figure 7. Comparison of computed withdrawal layer thickness.

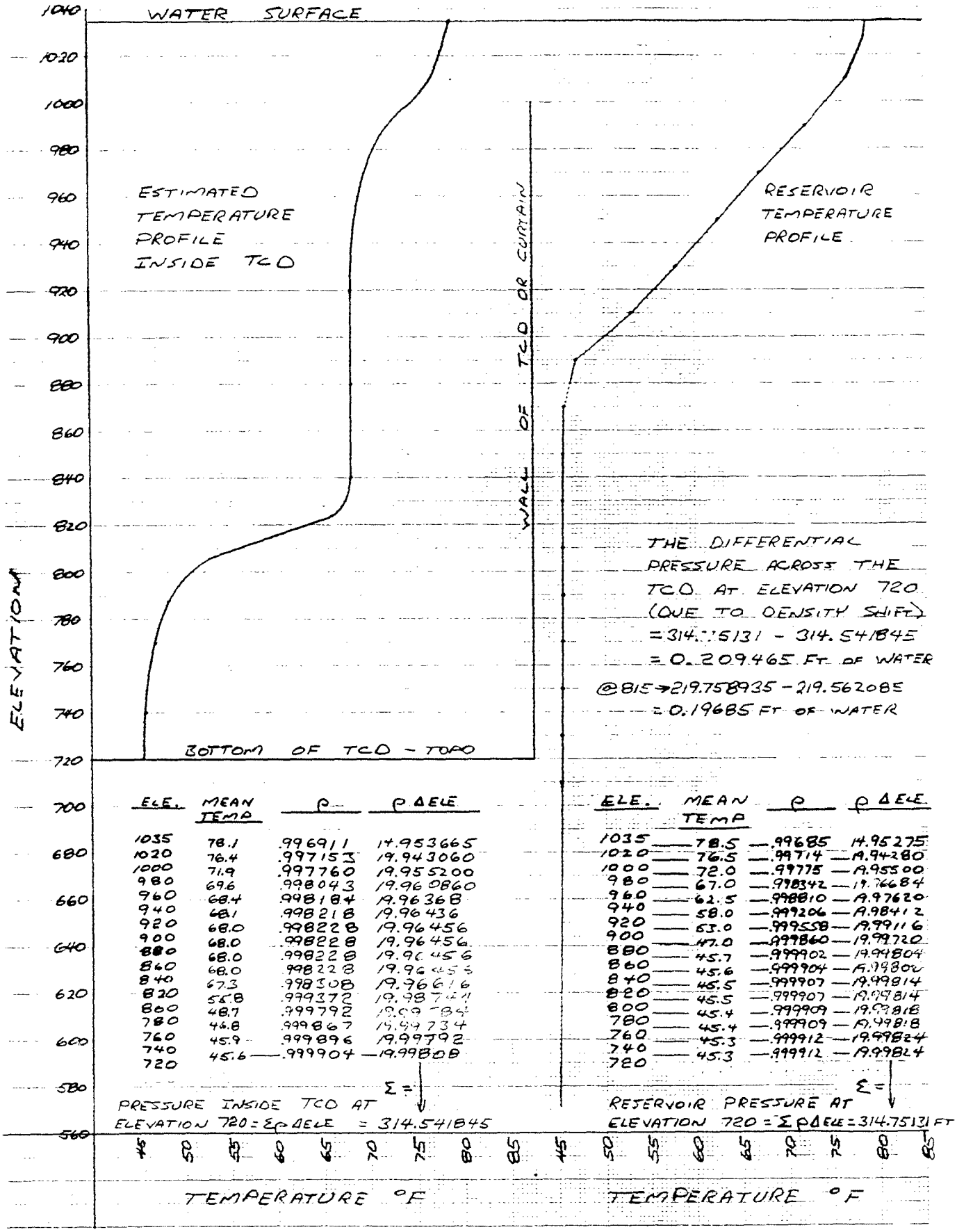


Figure 8. TCD operating with total overdraw and the corresponding temperature shifts that would result.

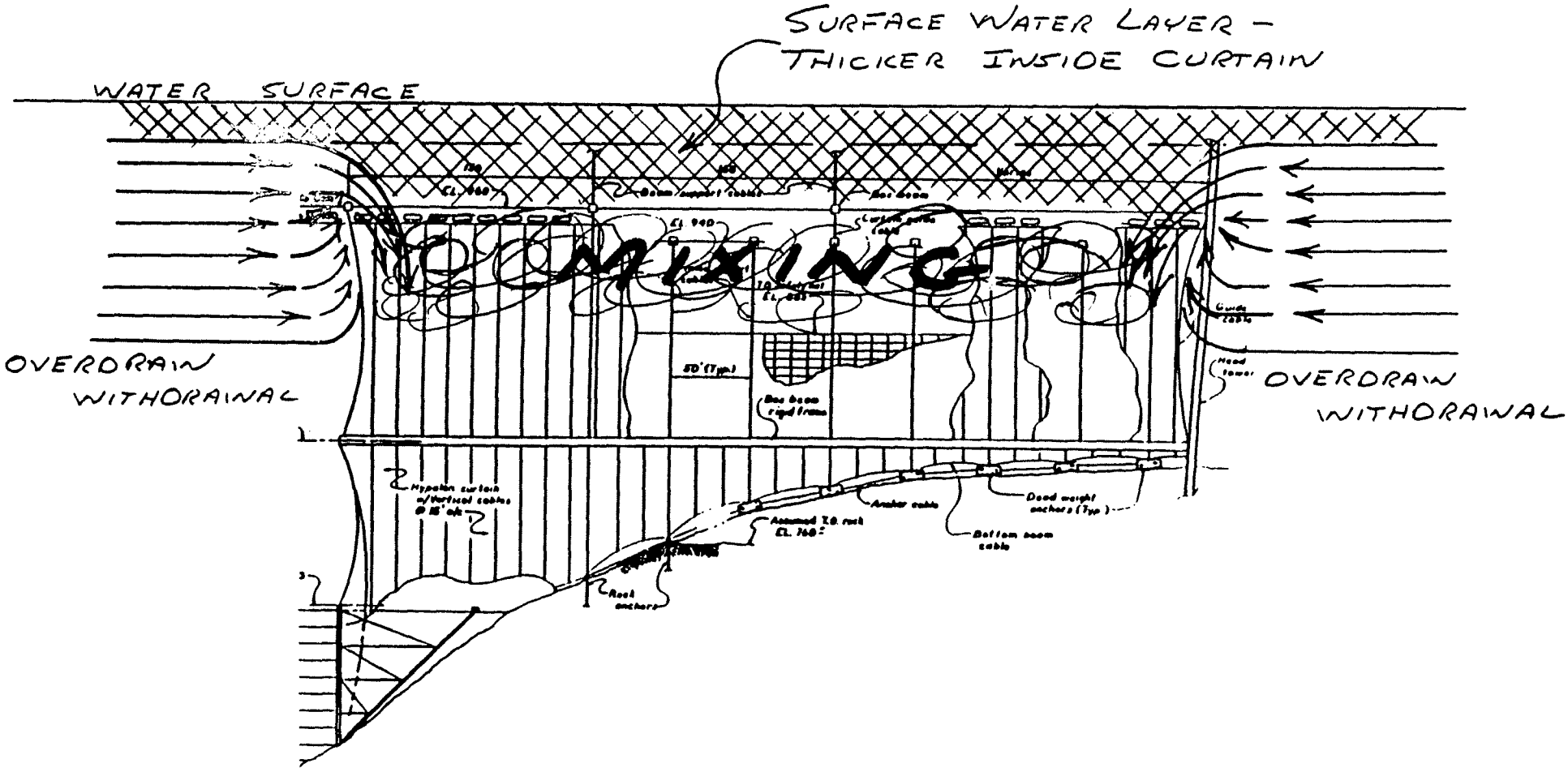


Figure 10. Schematic of mixing process which occurs when the withdrawal layer does not extend to the reservoir surface. This shear-induced mixing creates a thickened warm water layer inside the TCD.

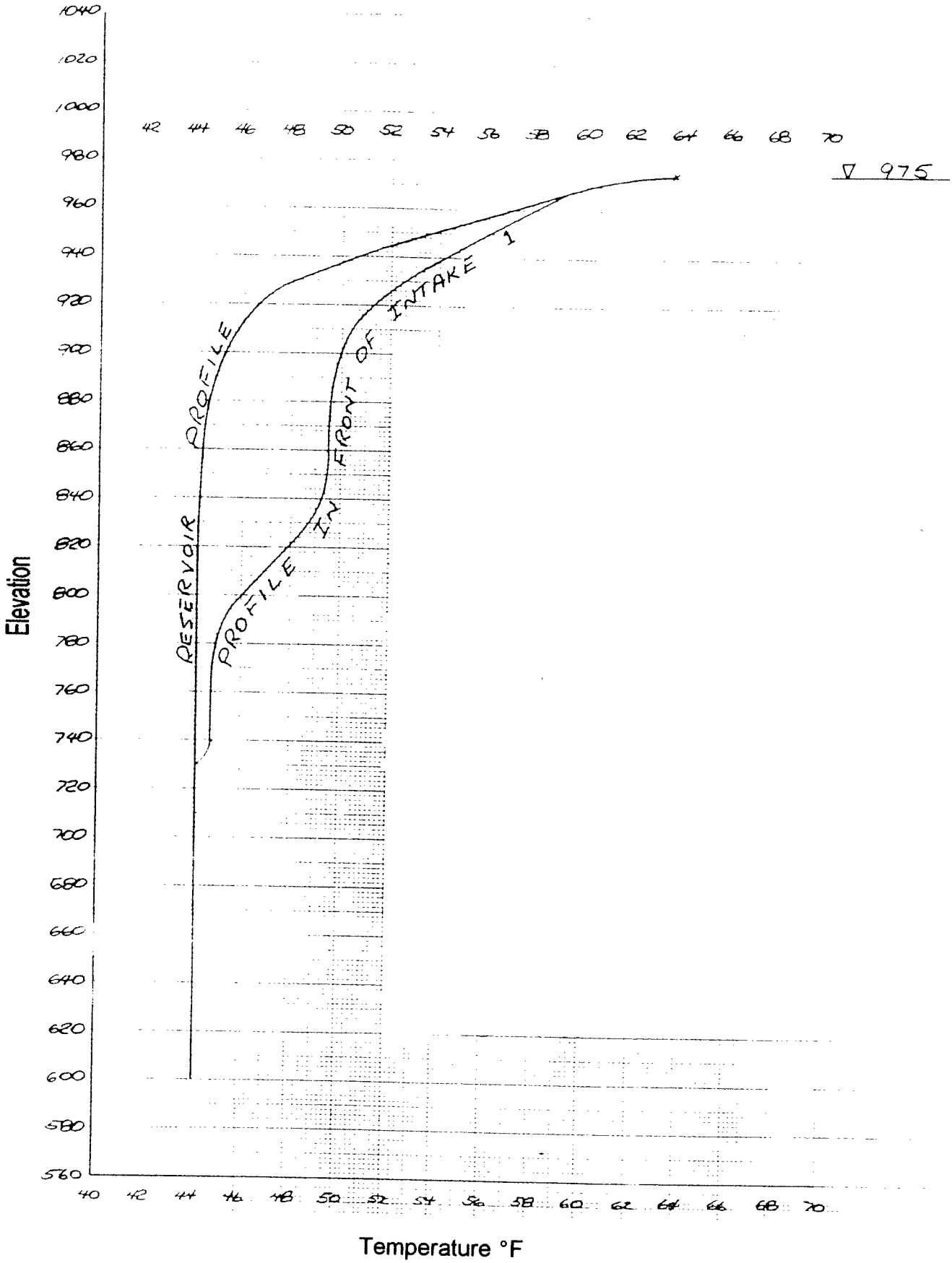


Figure 11. Typical overdraw profile.

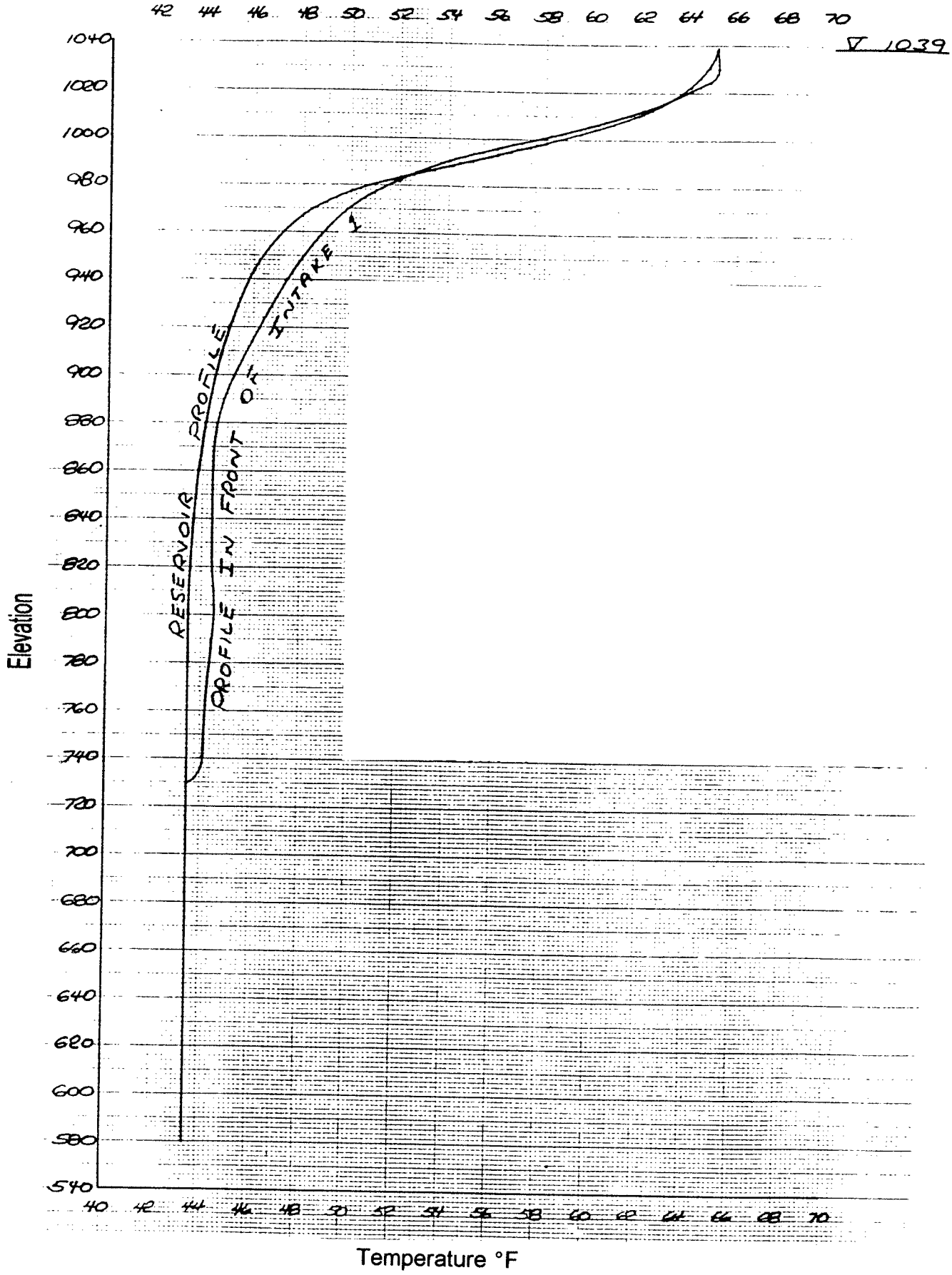


Figure 12. Typical underdraw - overdraw profiles - high reservoir.

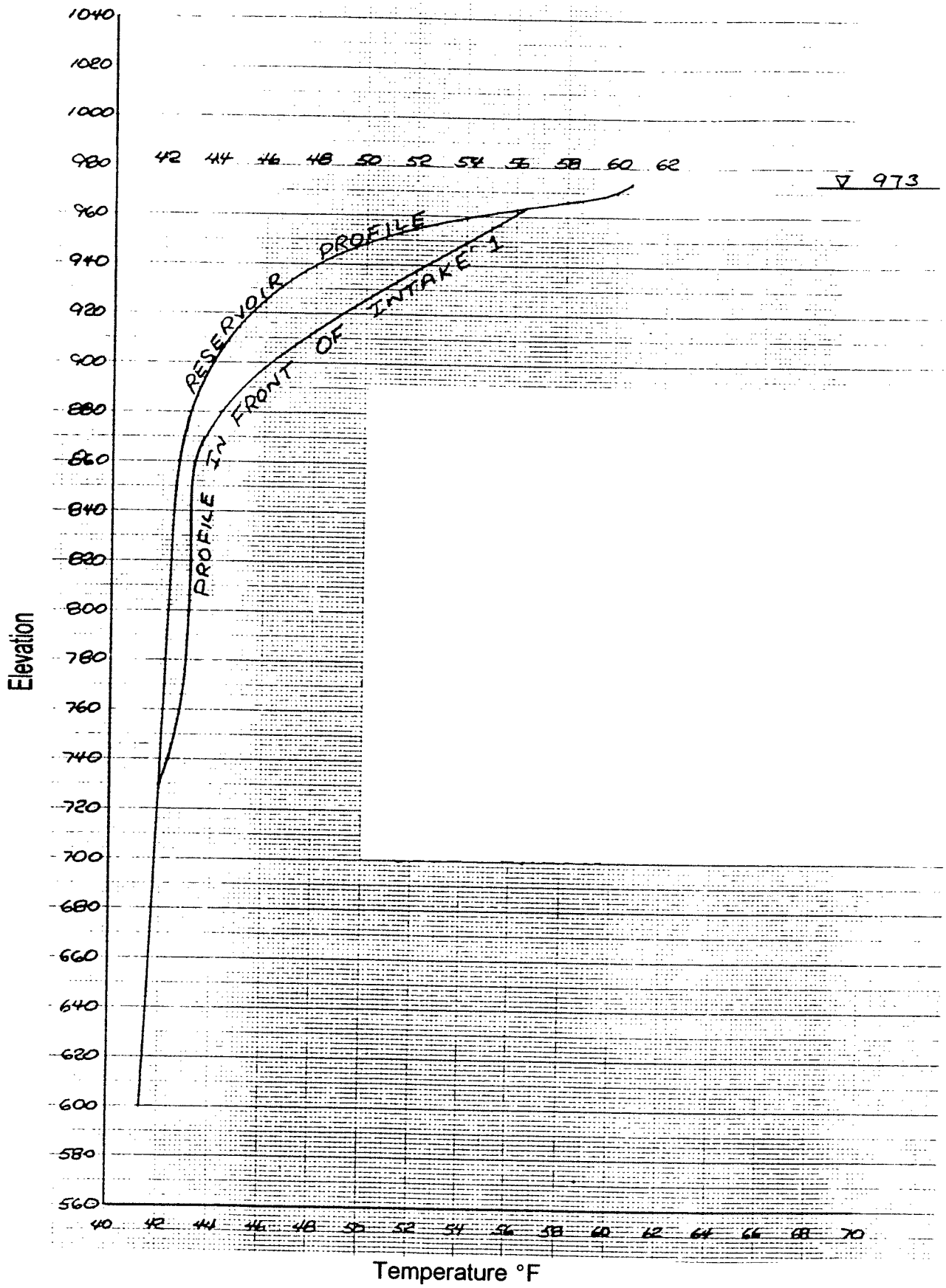


Figure 13. Typical underdraw - overdraw profiles - shallow submergence concept 4 curtain.

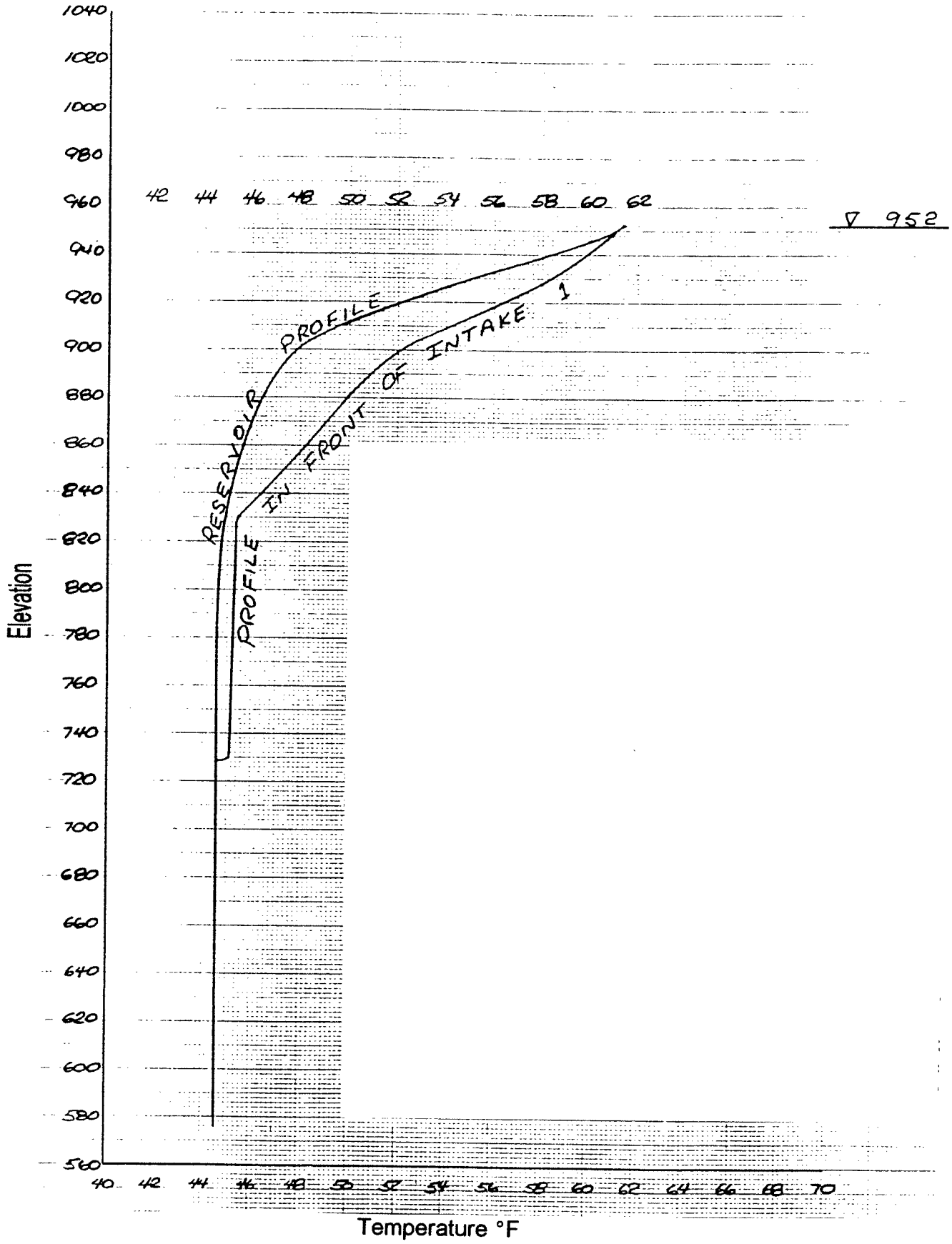


Figure 14. Typical underdraw - overdraw profiles - very shallow submergence.

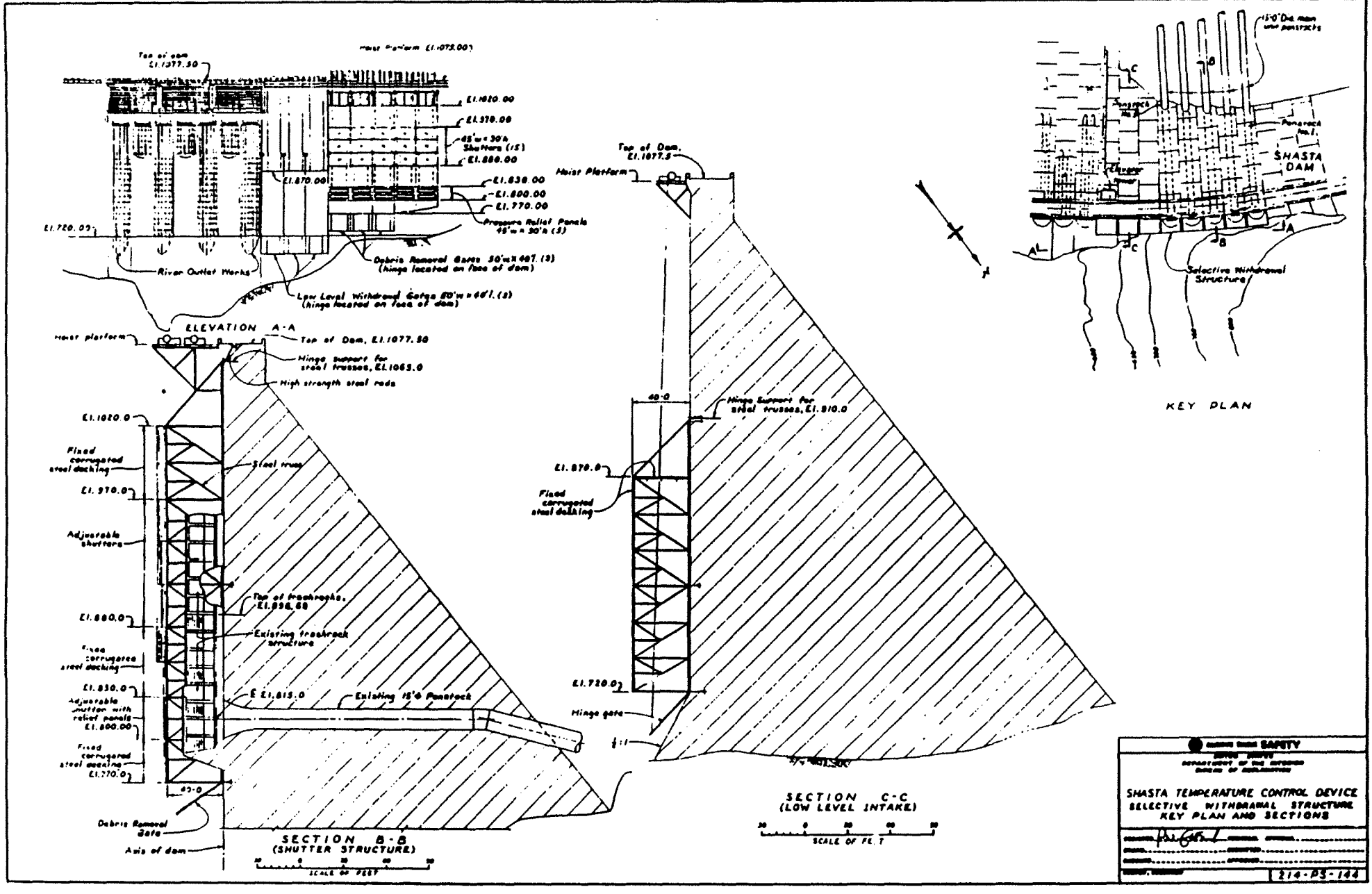


Figure 15. Shasta TCD selective withdrawal structure.

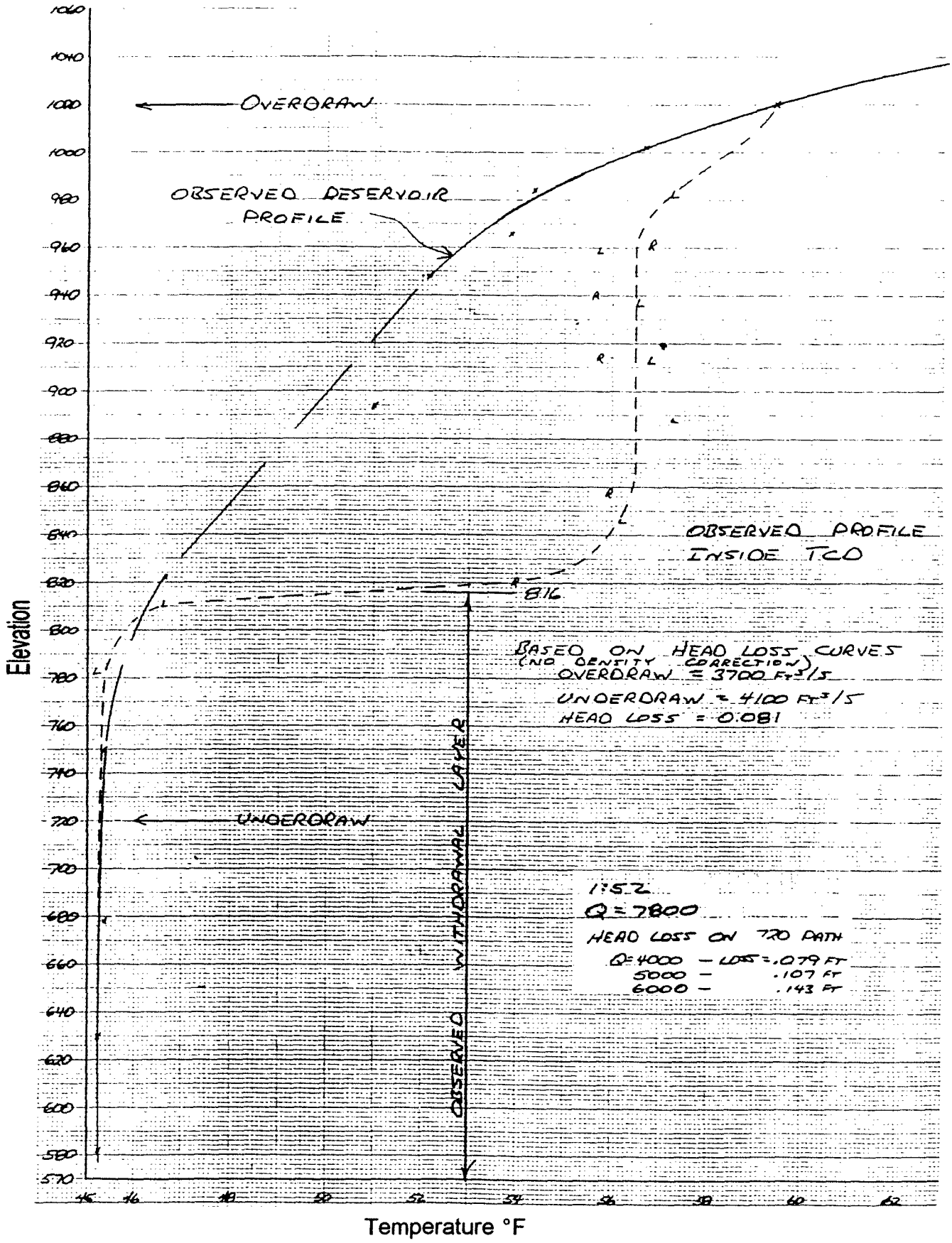


Figure 16. Comparison of reservoir and internal TCD temperature profiles for underflow (4,100 ft^3/sec) and overdraw (3,700 ft^3/sec).

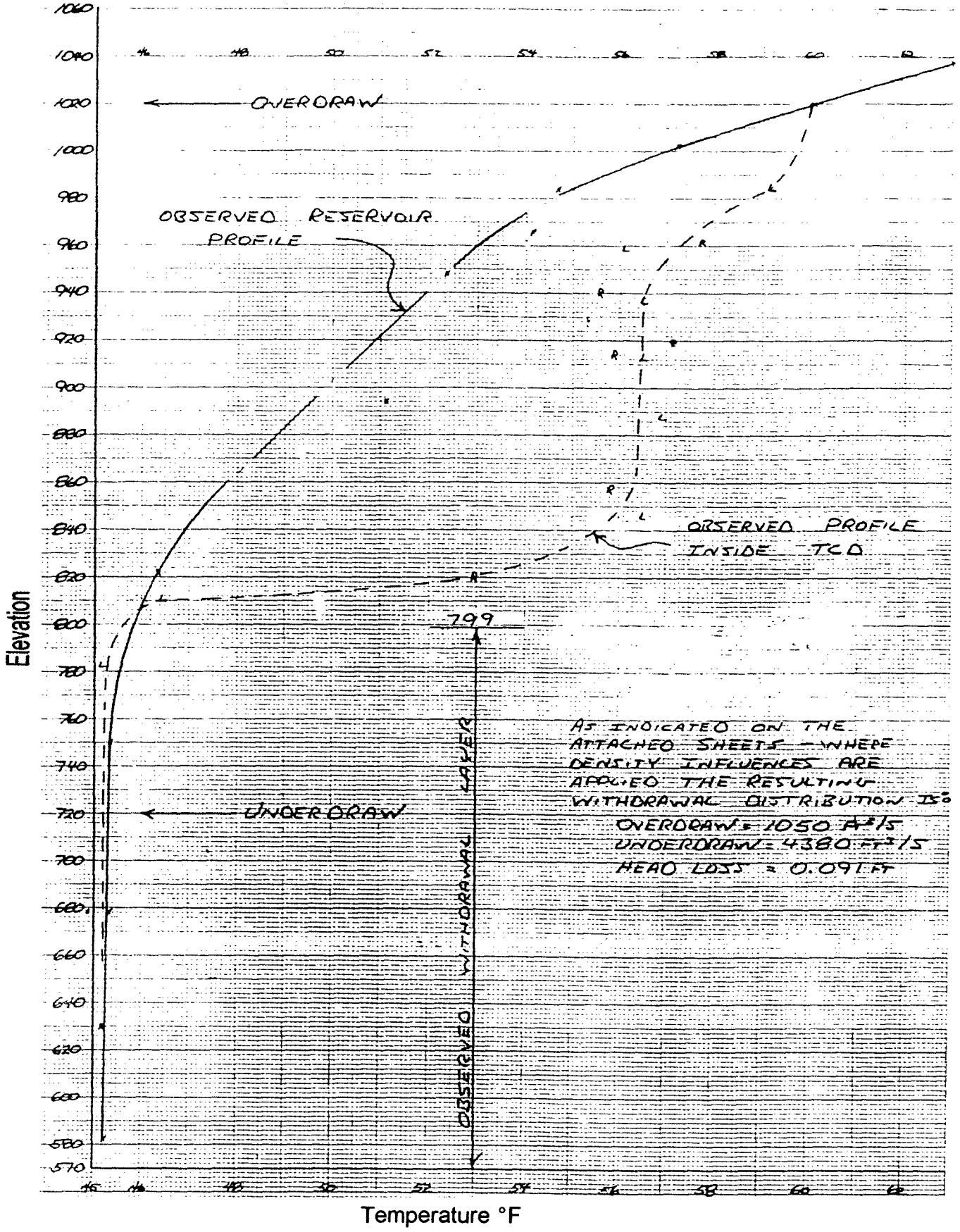


Figure 17. Comparison of reservoir and internal TCD temperature profiles for underflow (4,380 ft^3/sec) and overdraw (1,050 ft^3/sec).

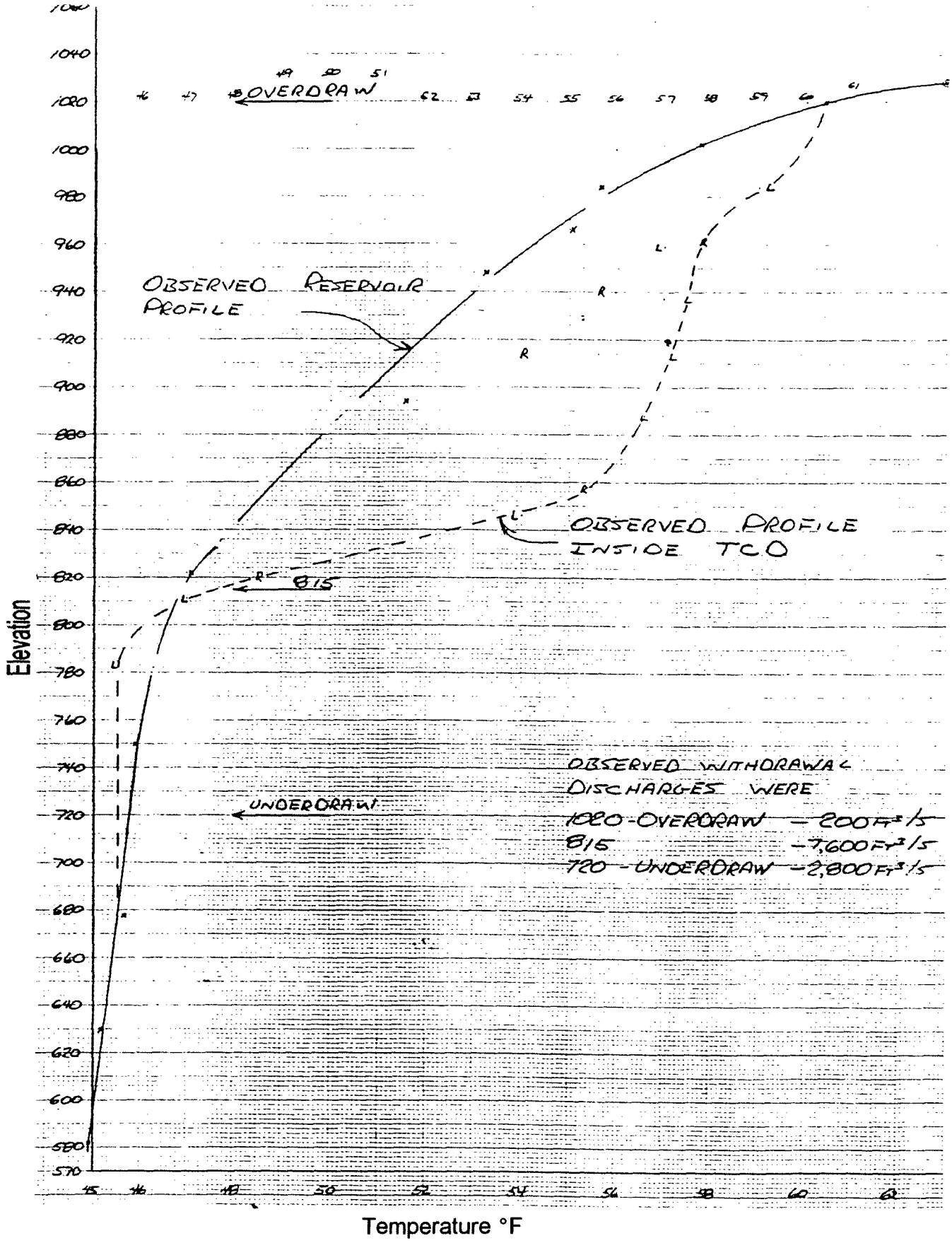


Figure 18. Comparison of reservoir and internal TCD temperature profiles for underflow (2,800 ft^3/sec), el. 815 withdrawal (7,600 ft^3/sec), and overdraw (3,700 ft^3/sec).

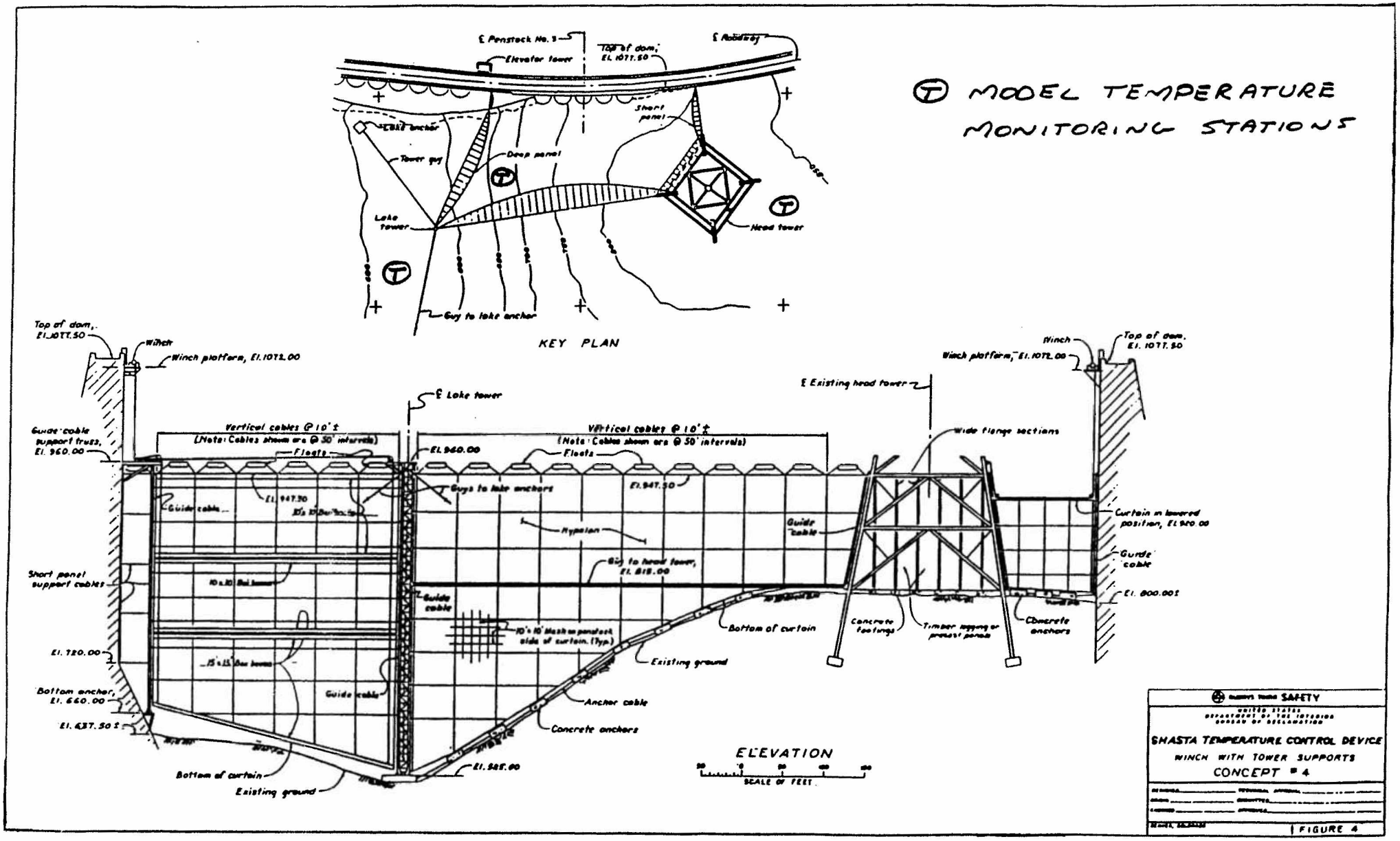
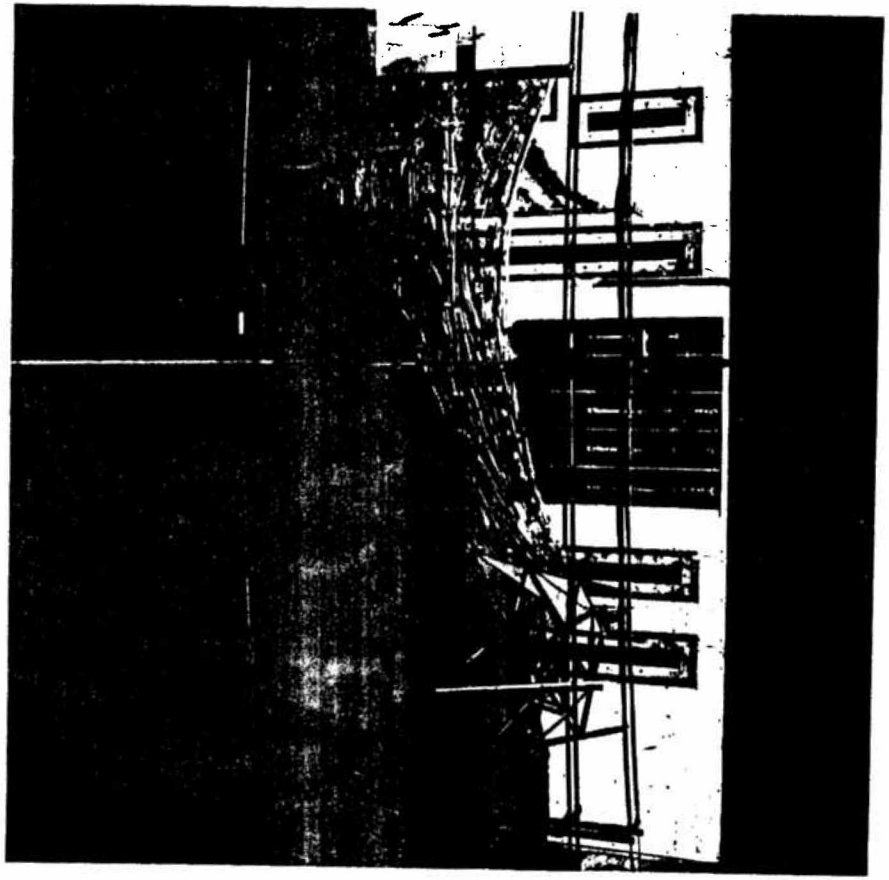


Figure 19. Shasta temperature control device winch with tower supports.



LARGE CURTAIN MODEL

FIGURE 20

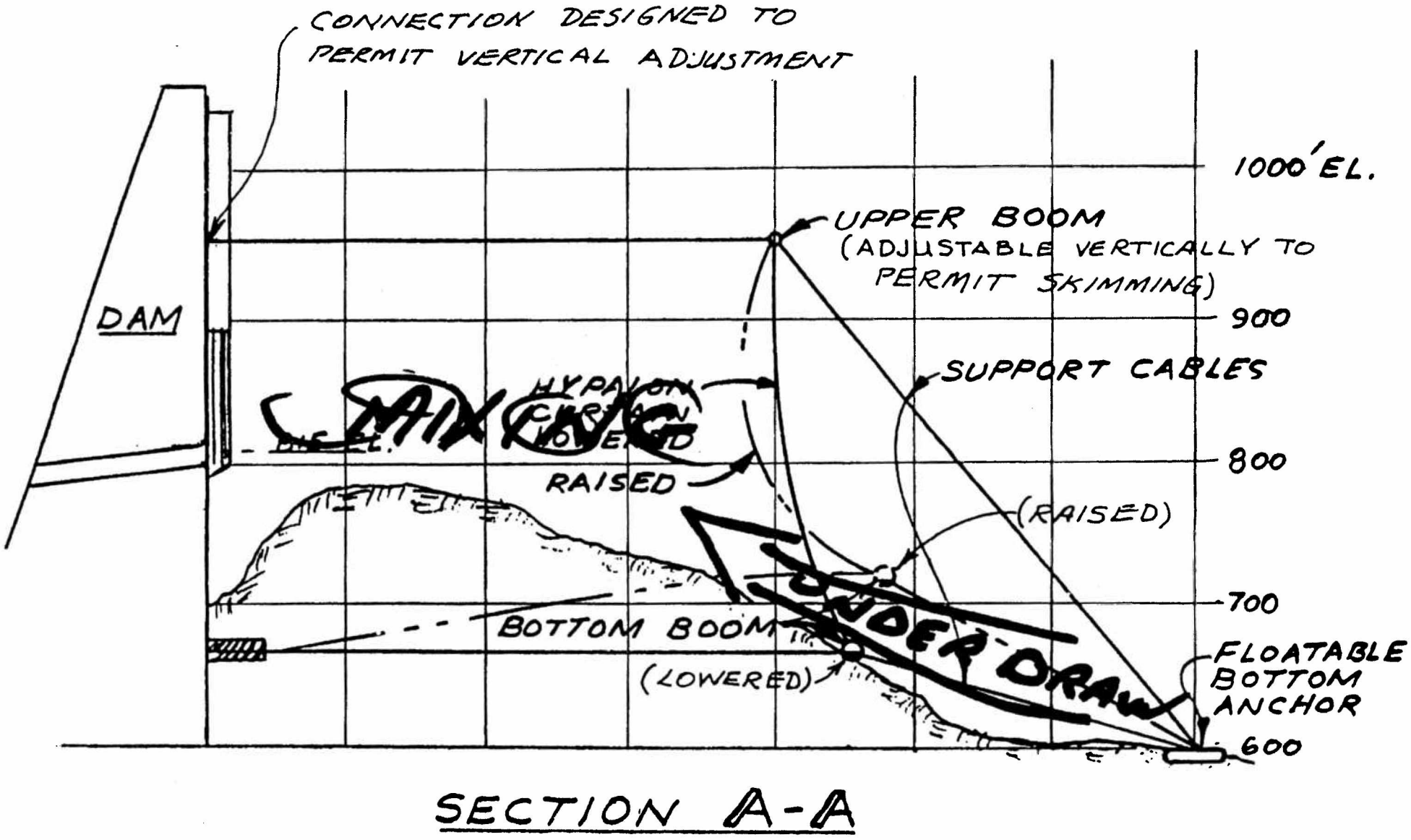
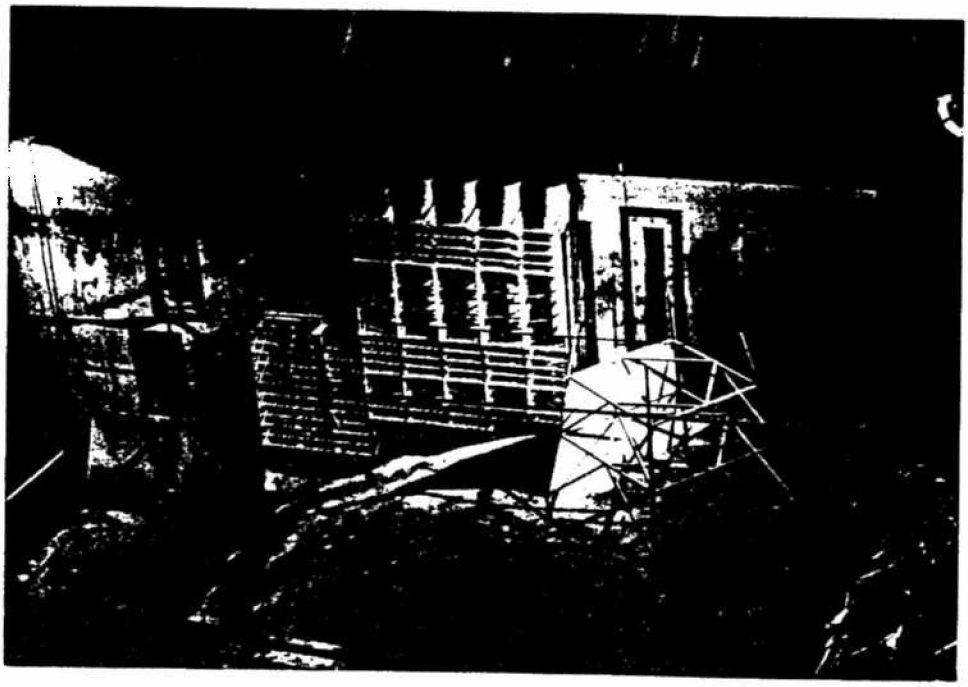
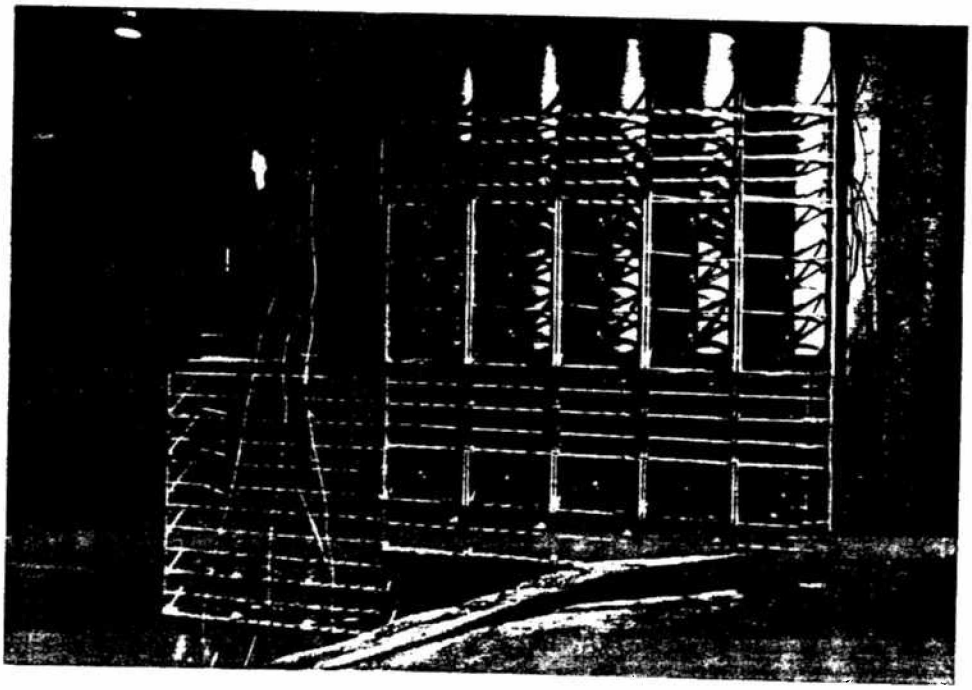


Figure 21. Shasta temperature curtain, cross section at river anchor.





MODELO RIGIO TCD

FIGURE 22

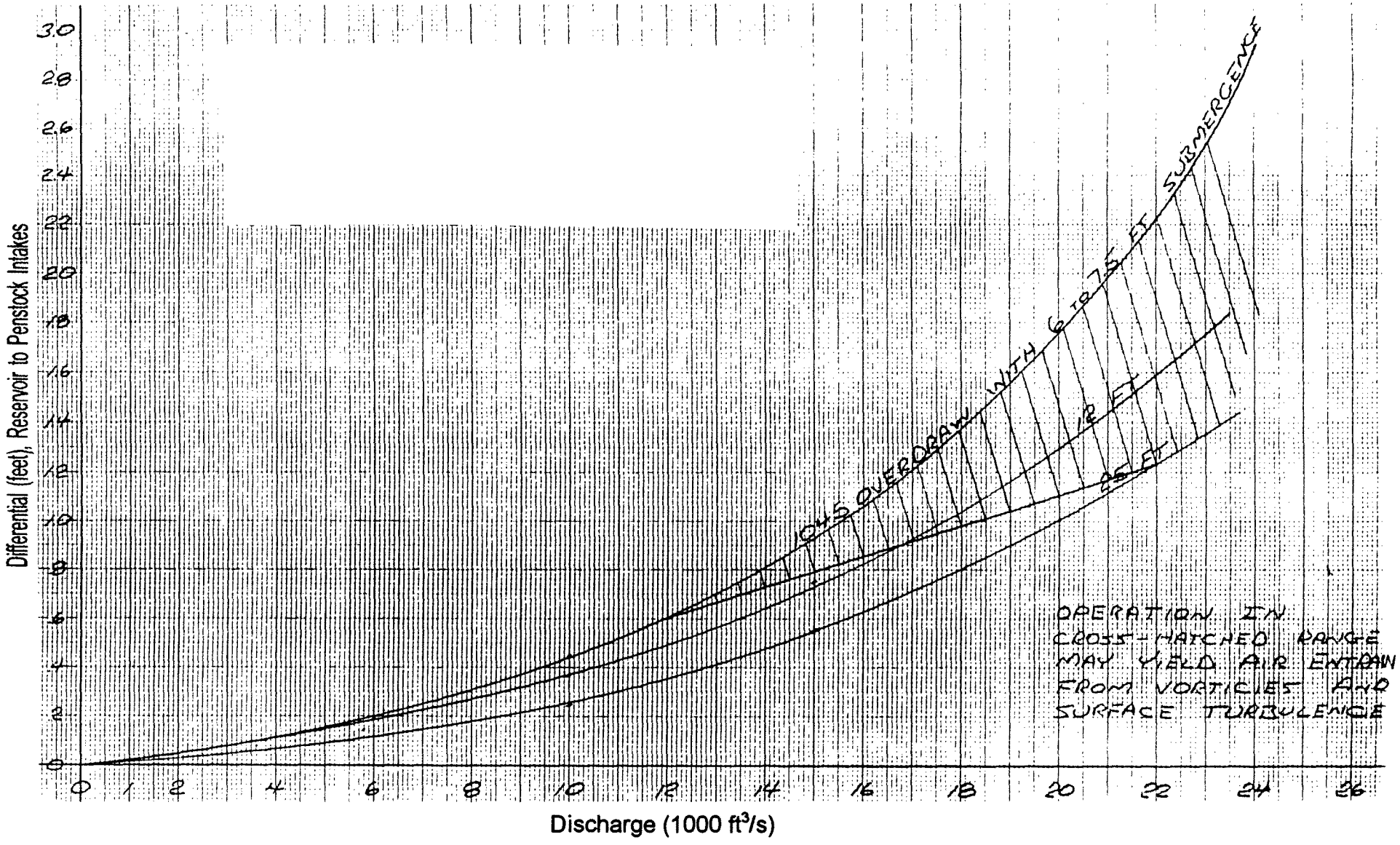


Figure 23. Shasta TCD: Differential-generated discharge with no density stratification. All five units operating (performance is independent of combination of operating units).

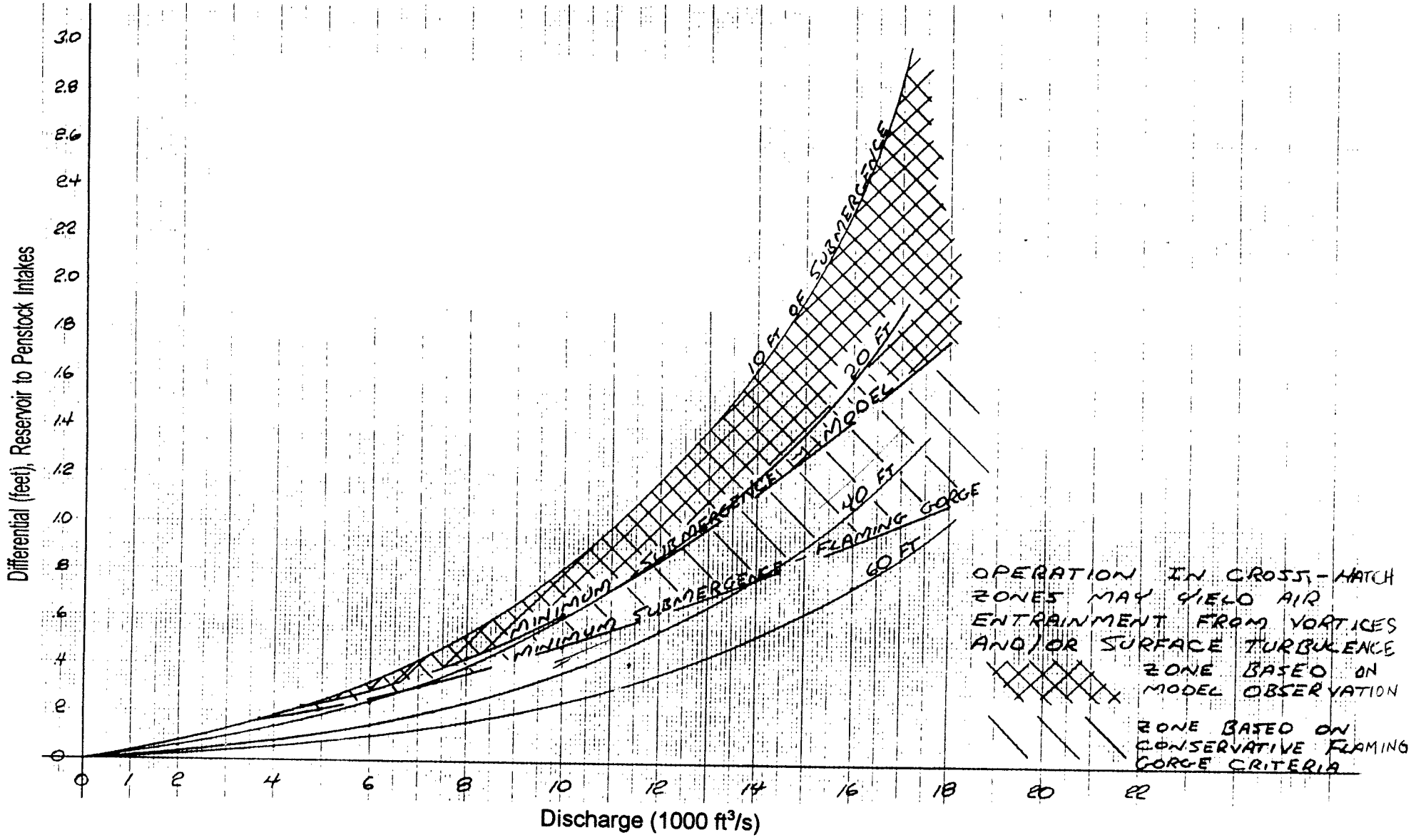


Figure 24. Shasta TCD: Differential-generated discharge with no density stratification. Overdraw over open gates (either the 1000 to 1045 level or the 900 to 945 level) - all five gates at the overdraw level are full open.

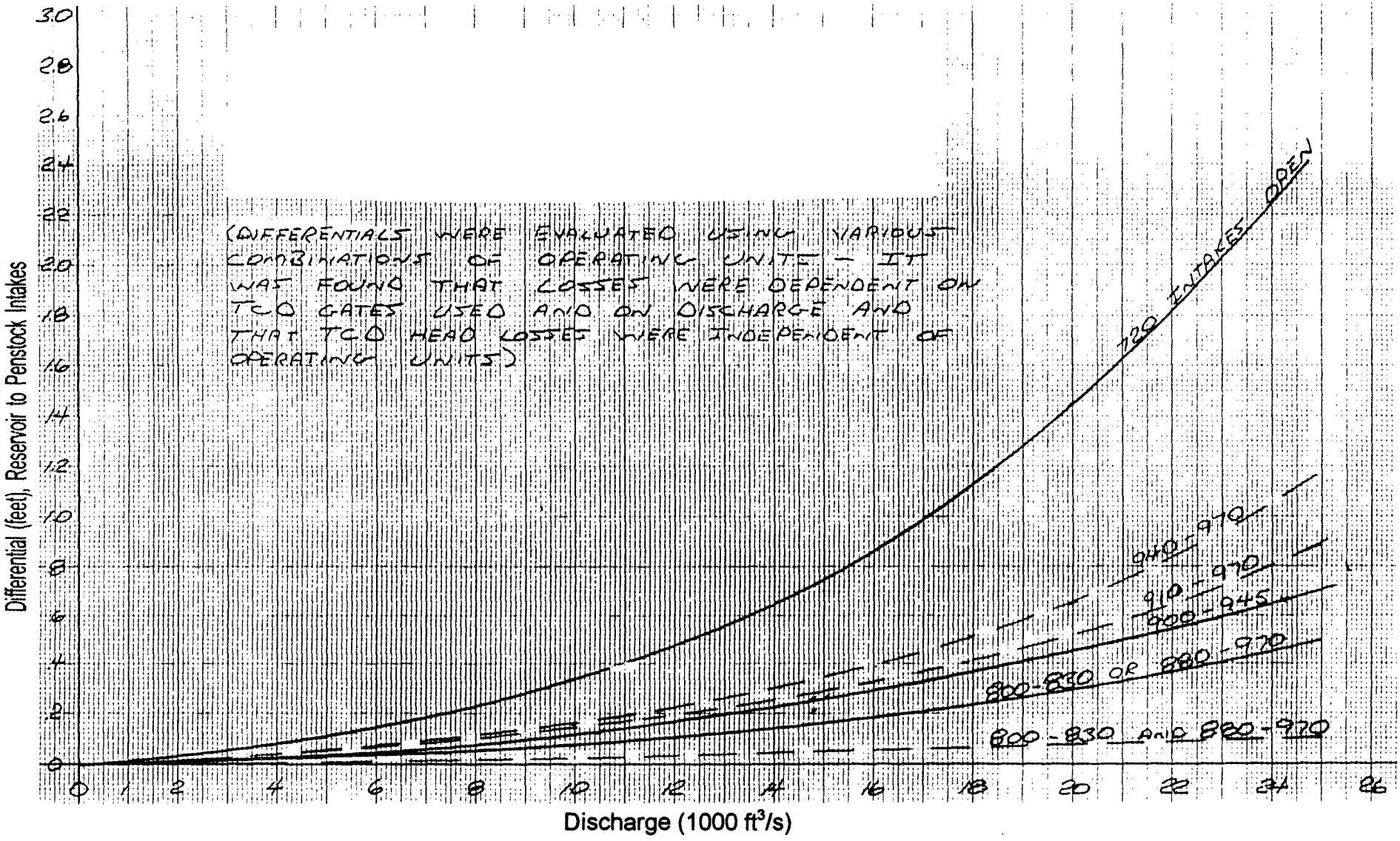


Figure 25. Shasta TCD: Differential-generated discharge with no density stratification. All five units operating, reservoir elevation between 980 and 1045.

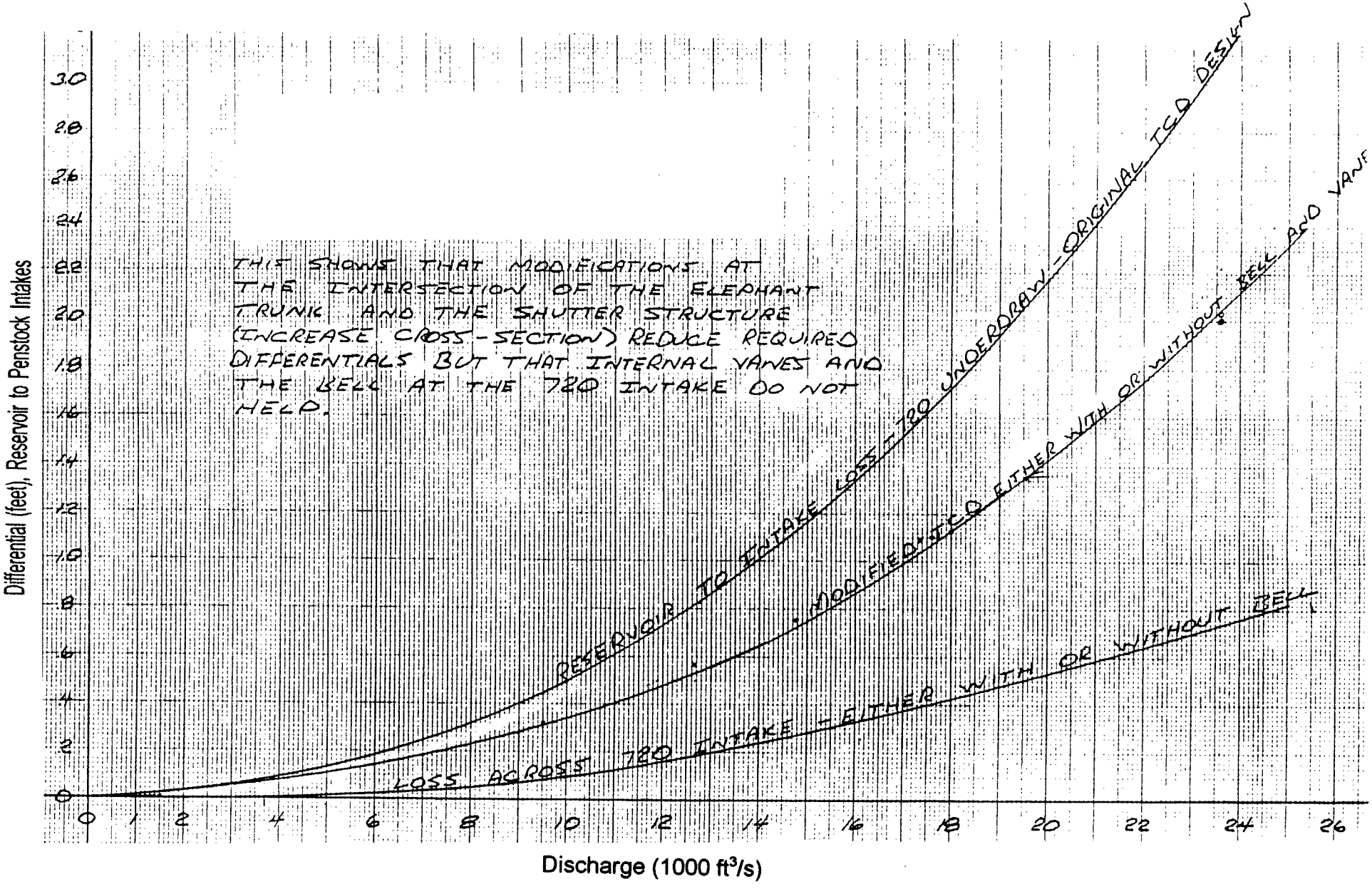


Figure 26. Shasta TCD: Differential-generated discharge with no density stratification. Original versus modified design.

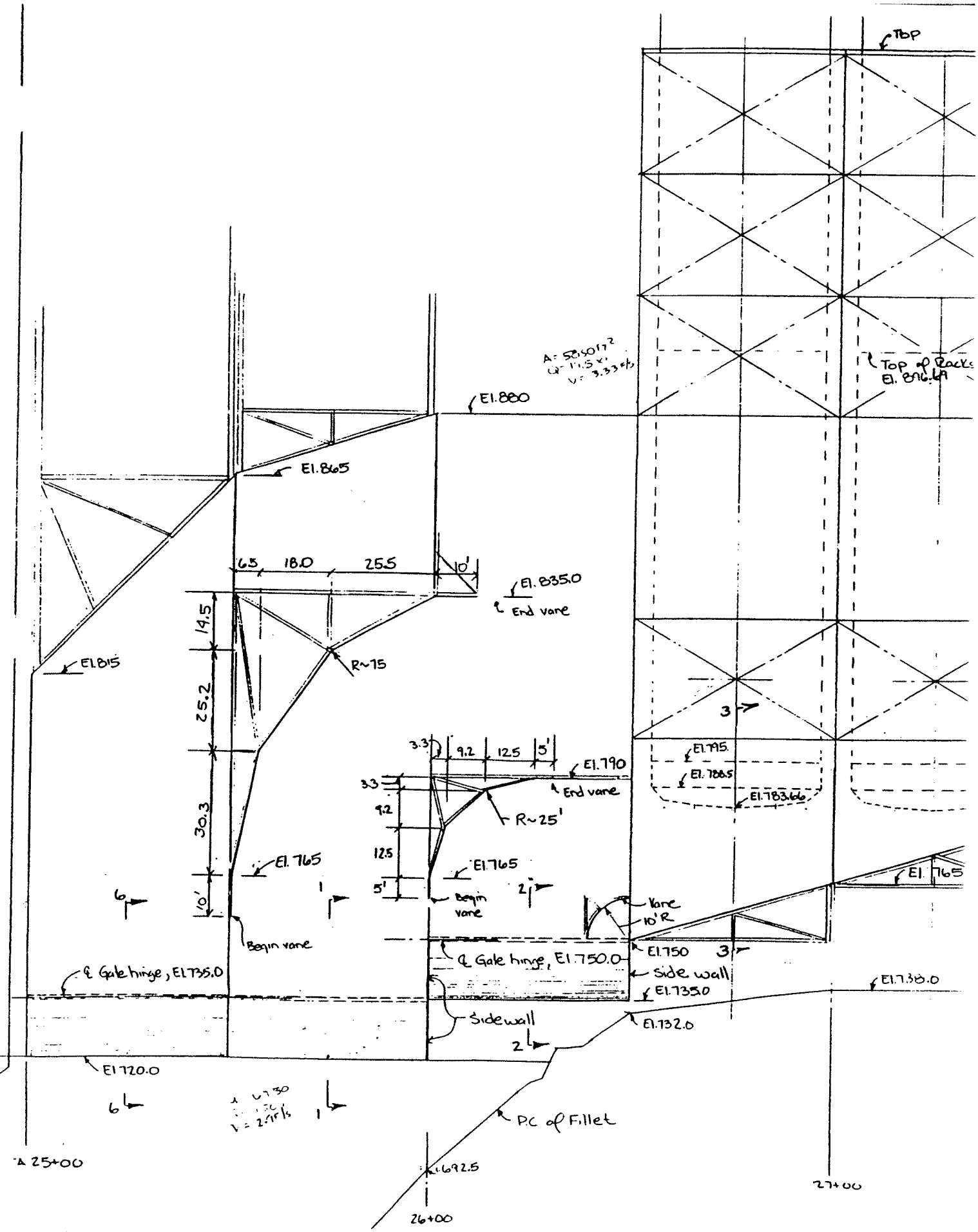


Figure 27. Sketch of bell-shaped intake design for the low-level intake. Guide vanes were evaluated to determine if the approach flow conditions could be improved.

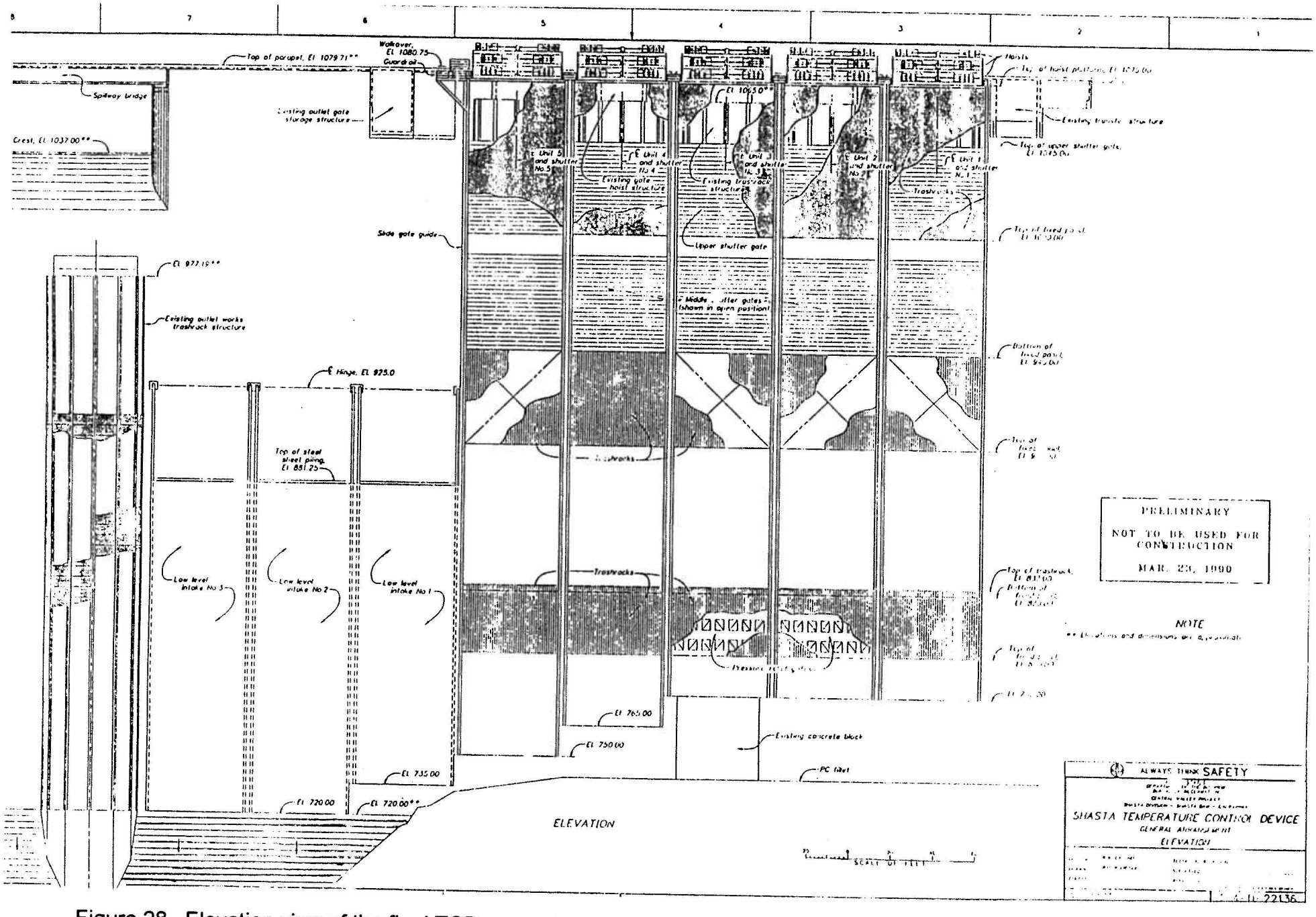


Figure 28. Elevation view of the final TCD concept.

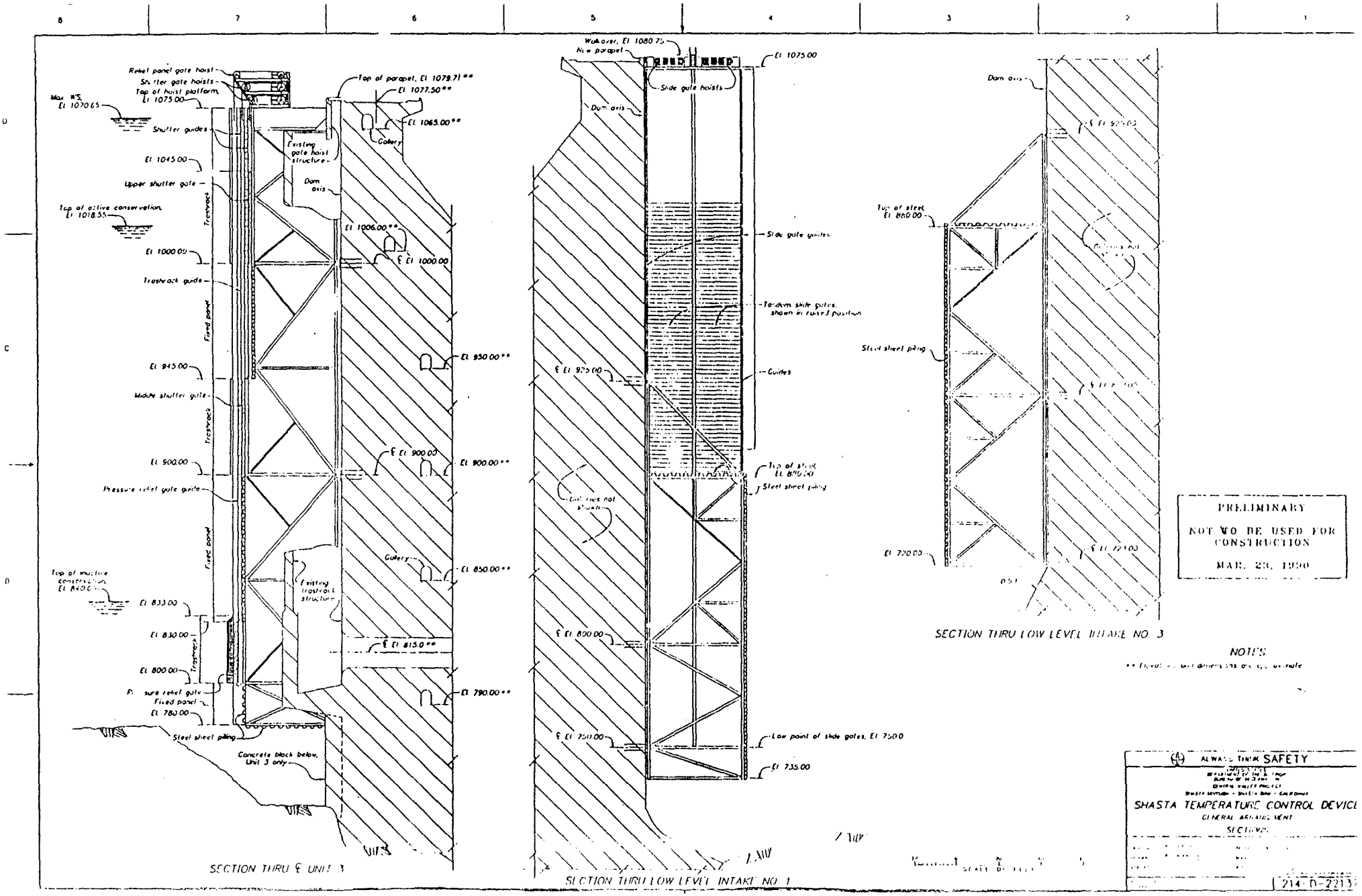


Figure 29. Cross-sectional views of the final TCD concept.

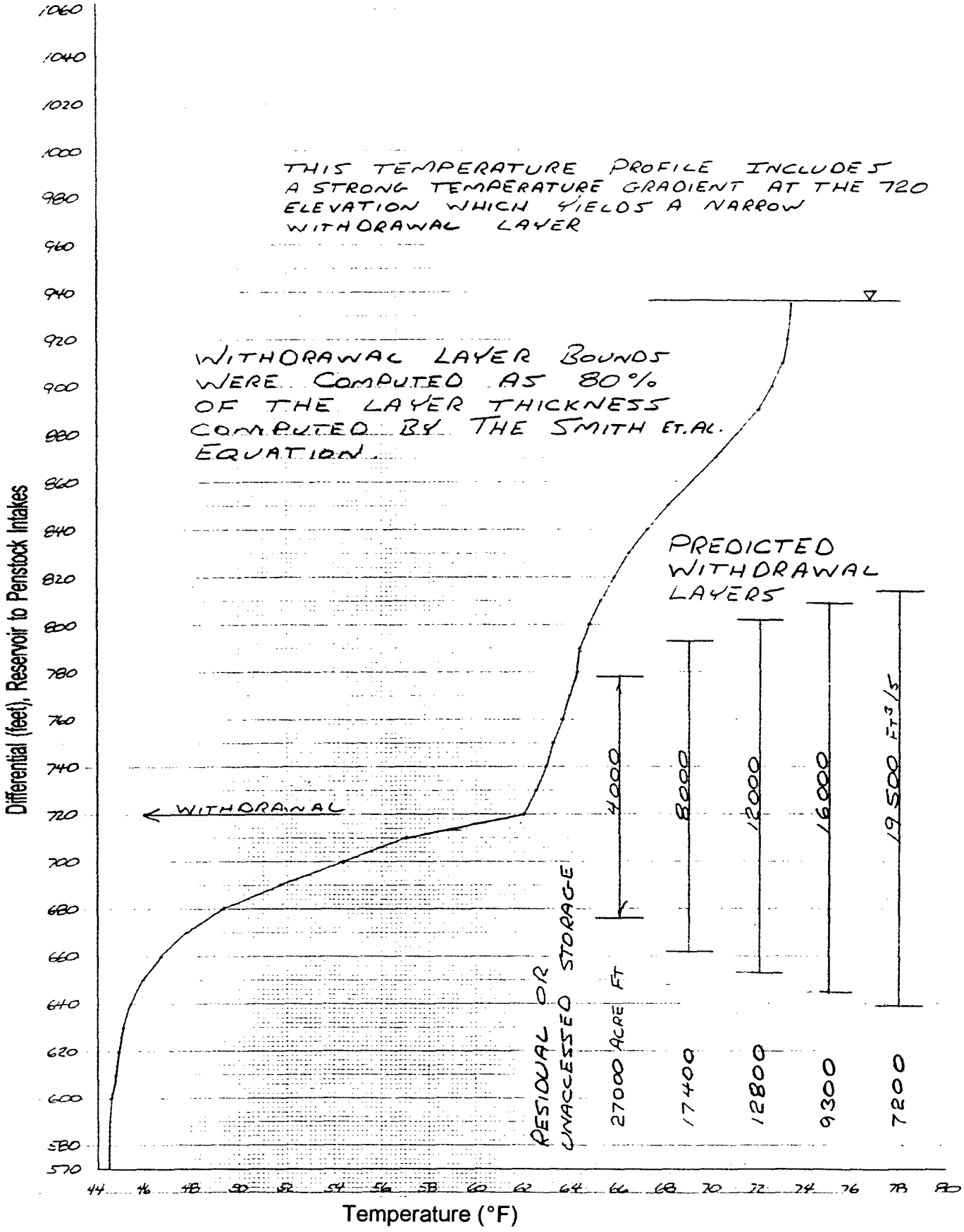


Figure 30. 1988: September temperature profile computer model predicted releases made from 955, 925, 895, 815, and 710 as the year progressed.

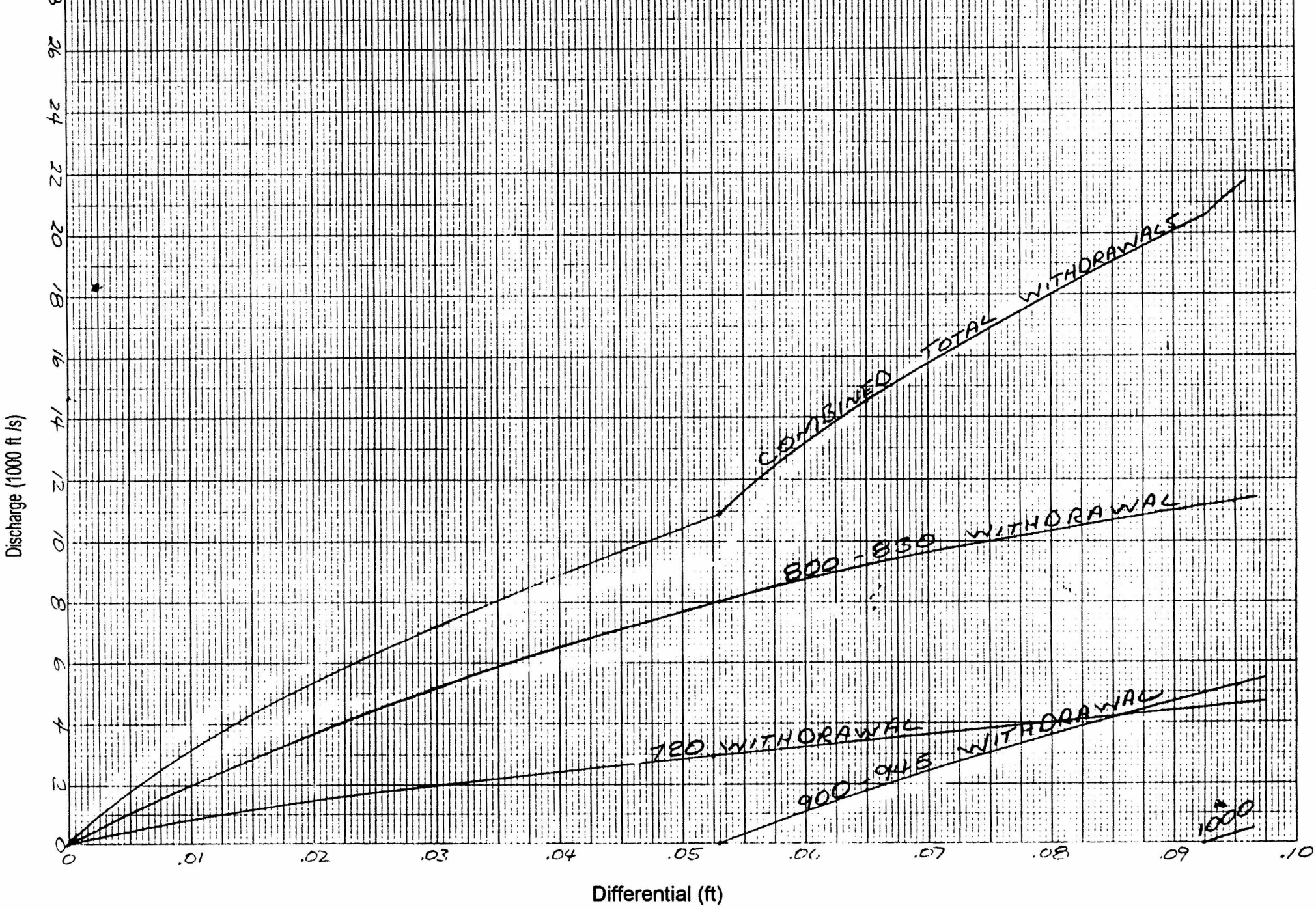


Figure 31. Plot of TCD selective withdrawal discharges versus head differential.

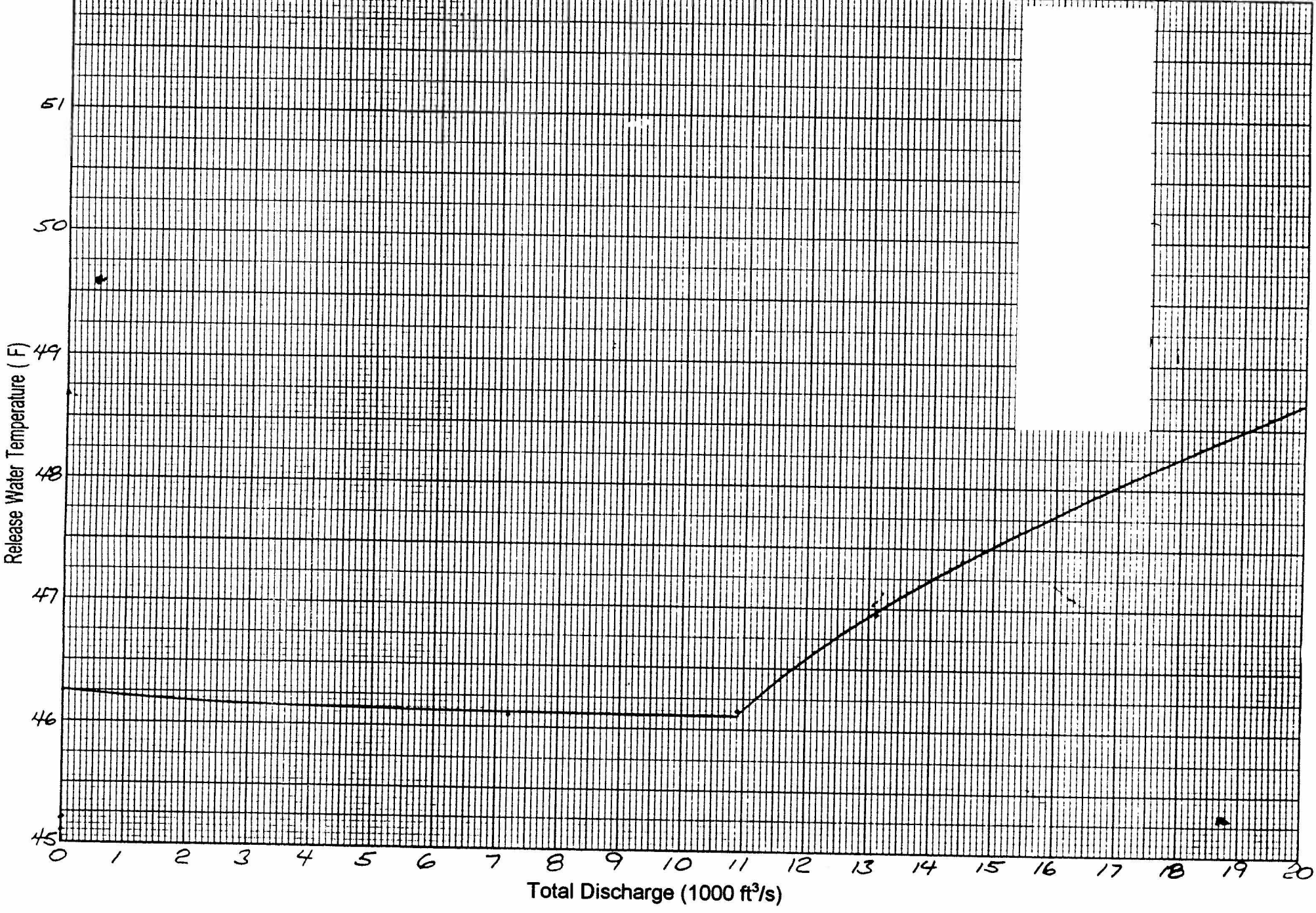
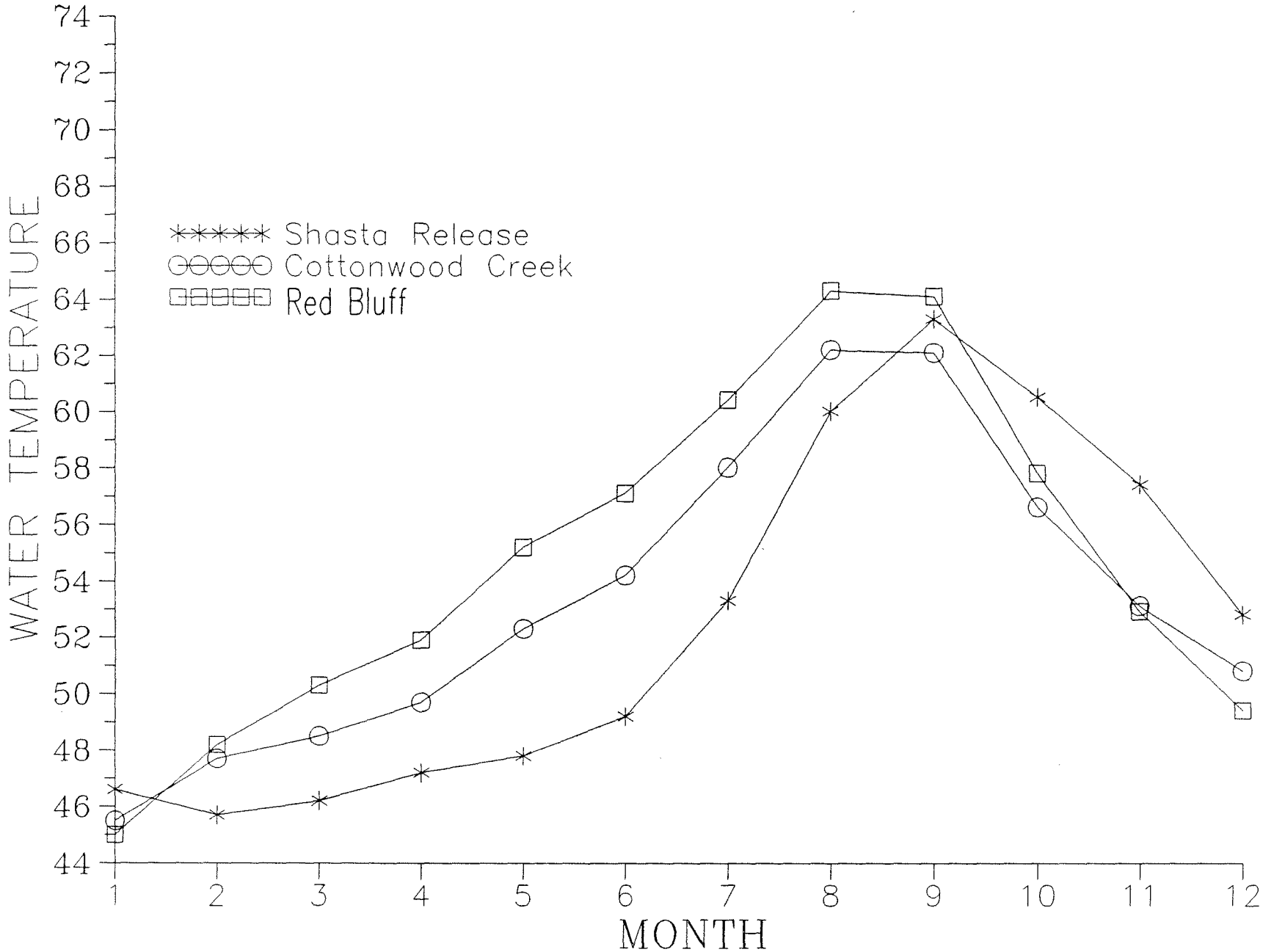


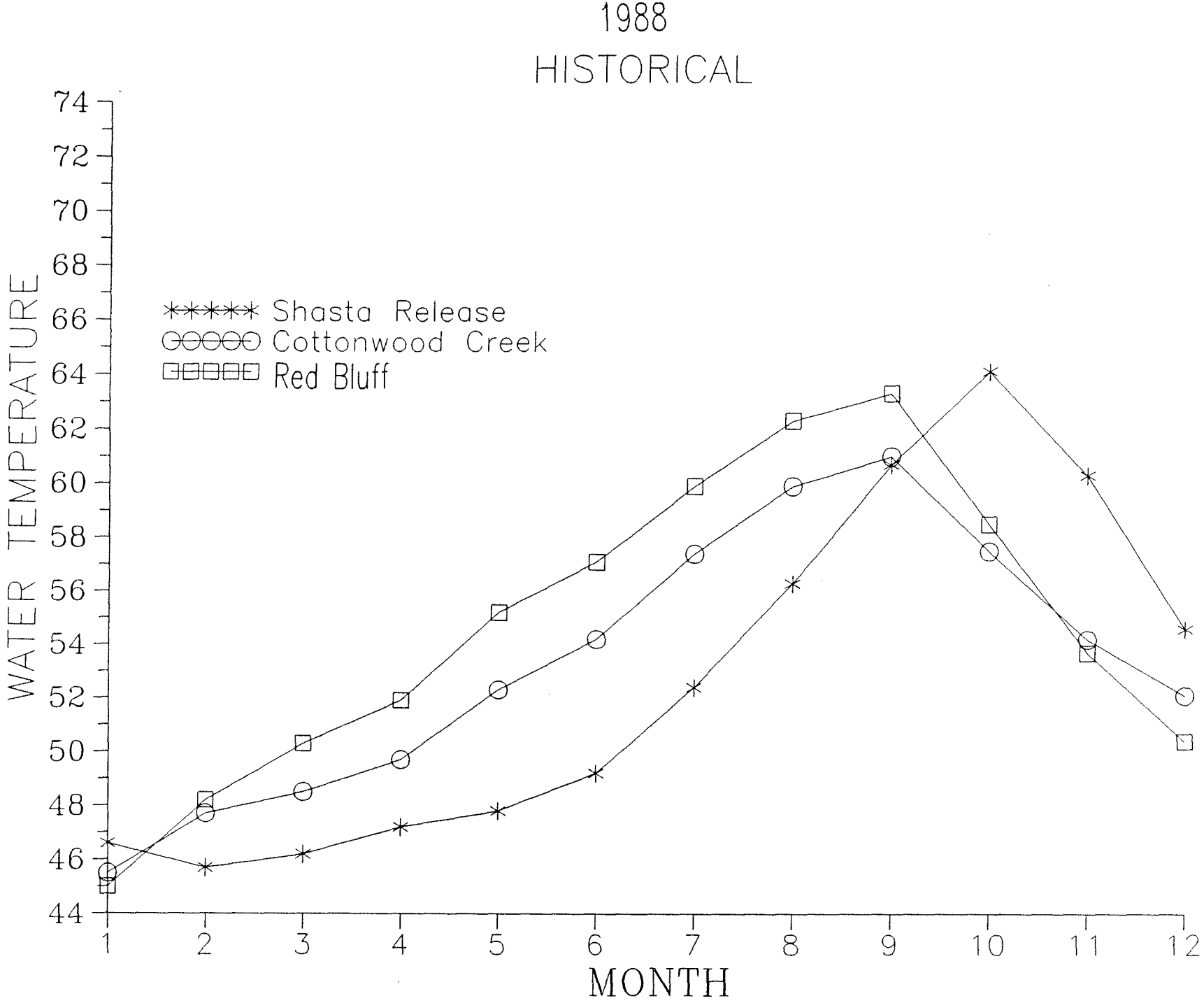
Figure 32. Reservoir temperature profile from August 1975 computer model, all gates open.

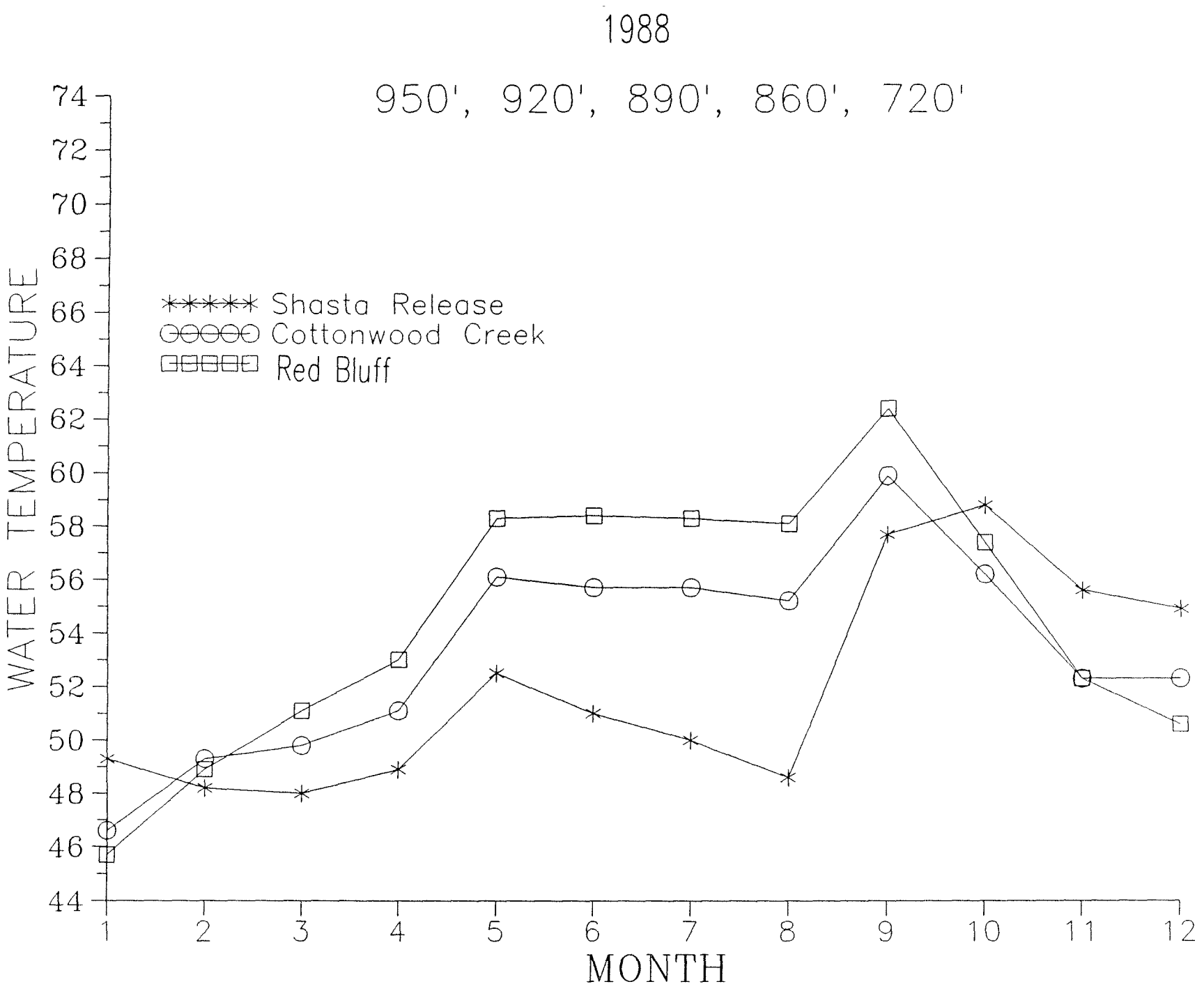
Appendix - Computer Model Results

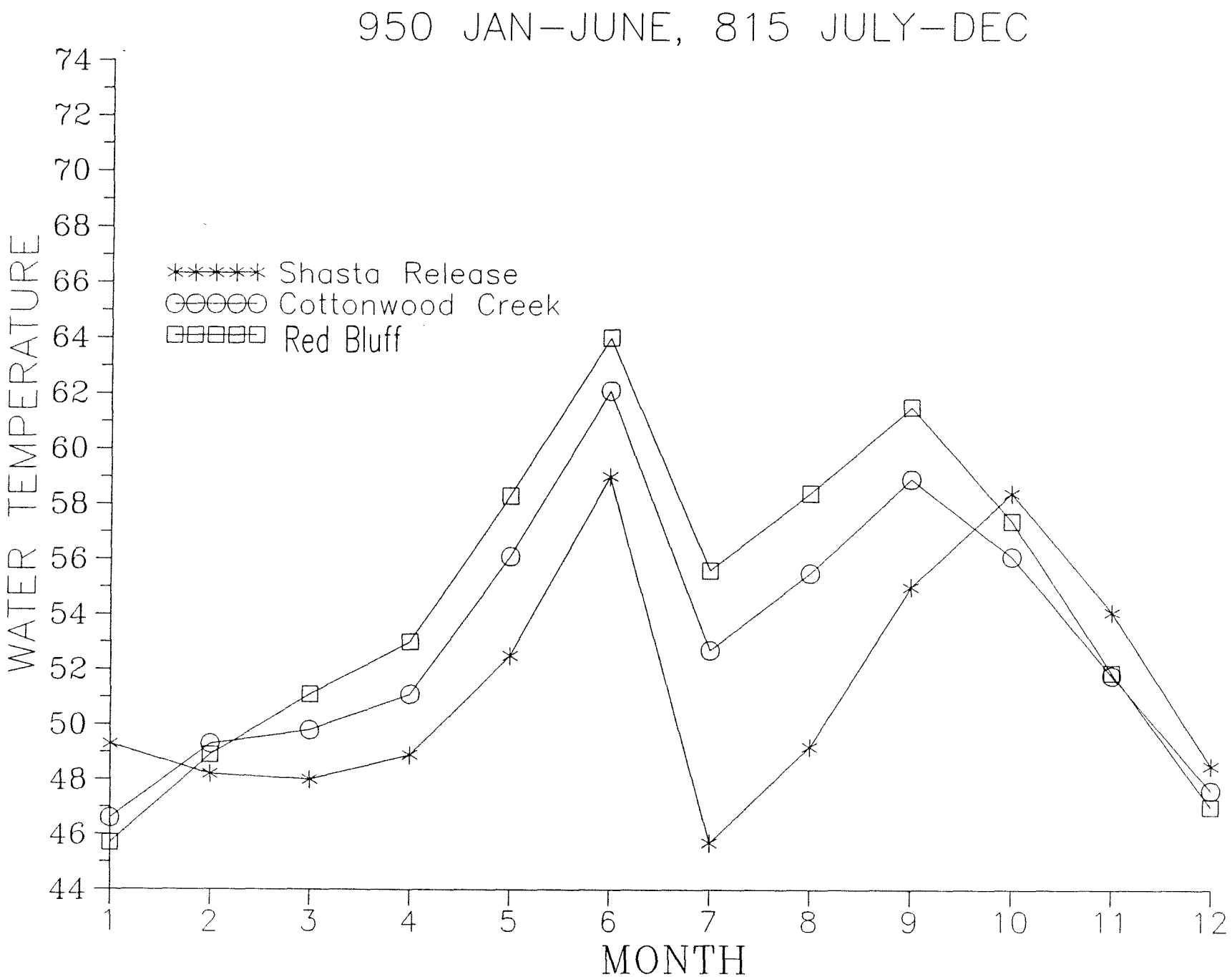
1988

ALL RELEASES FROM THE 815 LEVEL



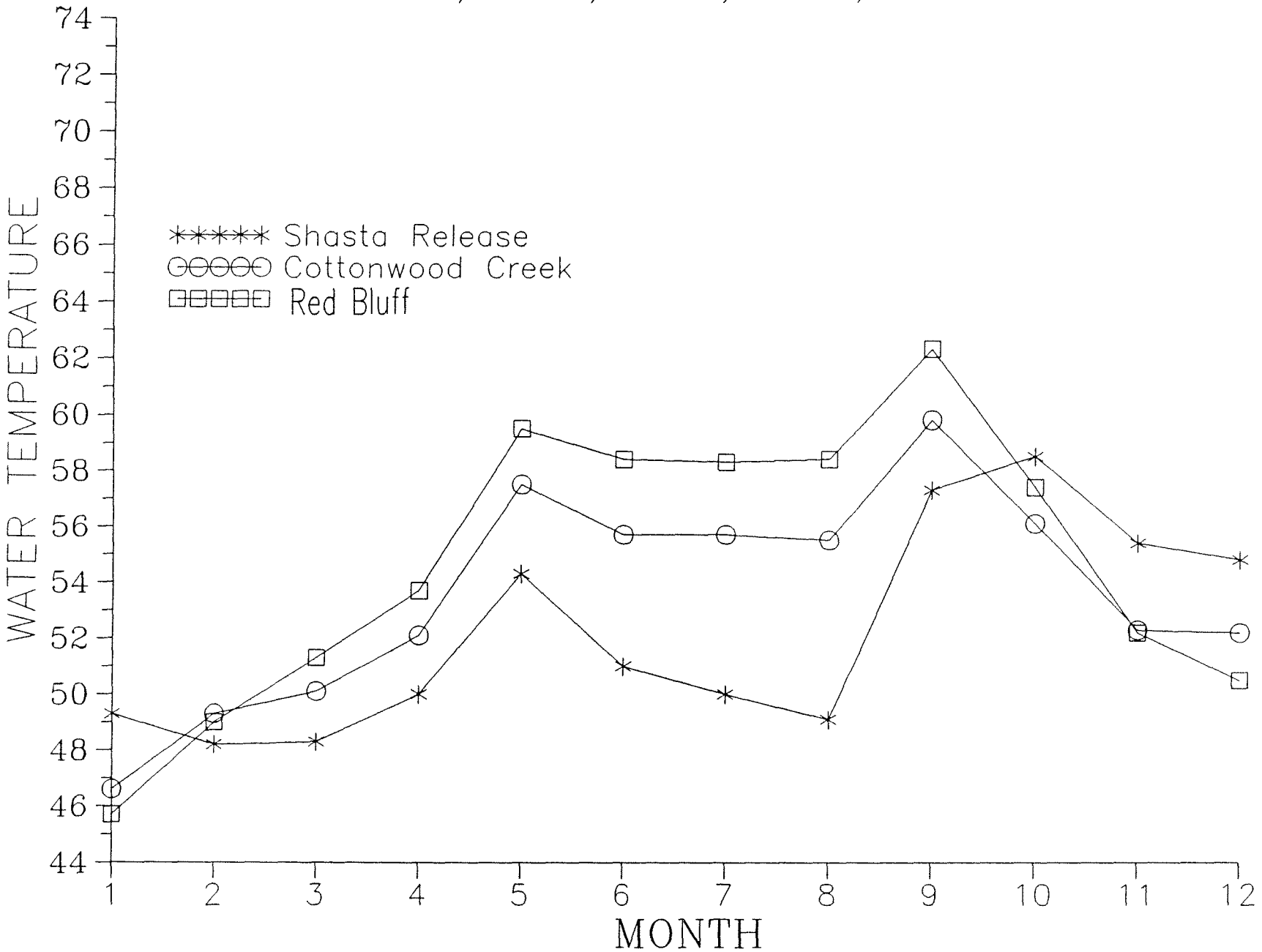

1988
HISTORICAL
WATER TEMPERATURE
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44
Shasta Release
Cottonwood Creek
Red Bluff
1
2
3
4
5
6
7
8
9
10
11
12
MONTH


1988
950', 920', 890', 860', 720'
WATER TEMPERATURE
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44
Shasta Release
Cottonwood Creek
Red Bluff
1
2
3
4
5
6
7
8
9
10
11
12
MONTH

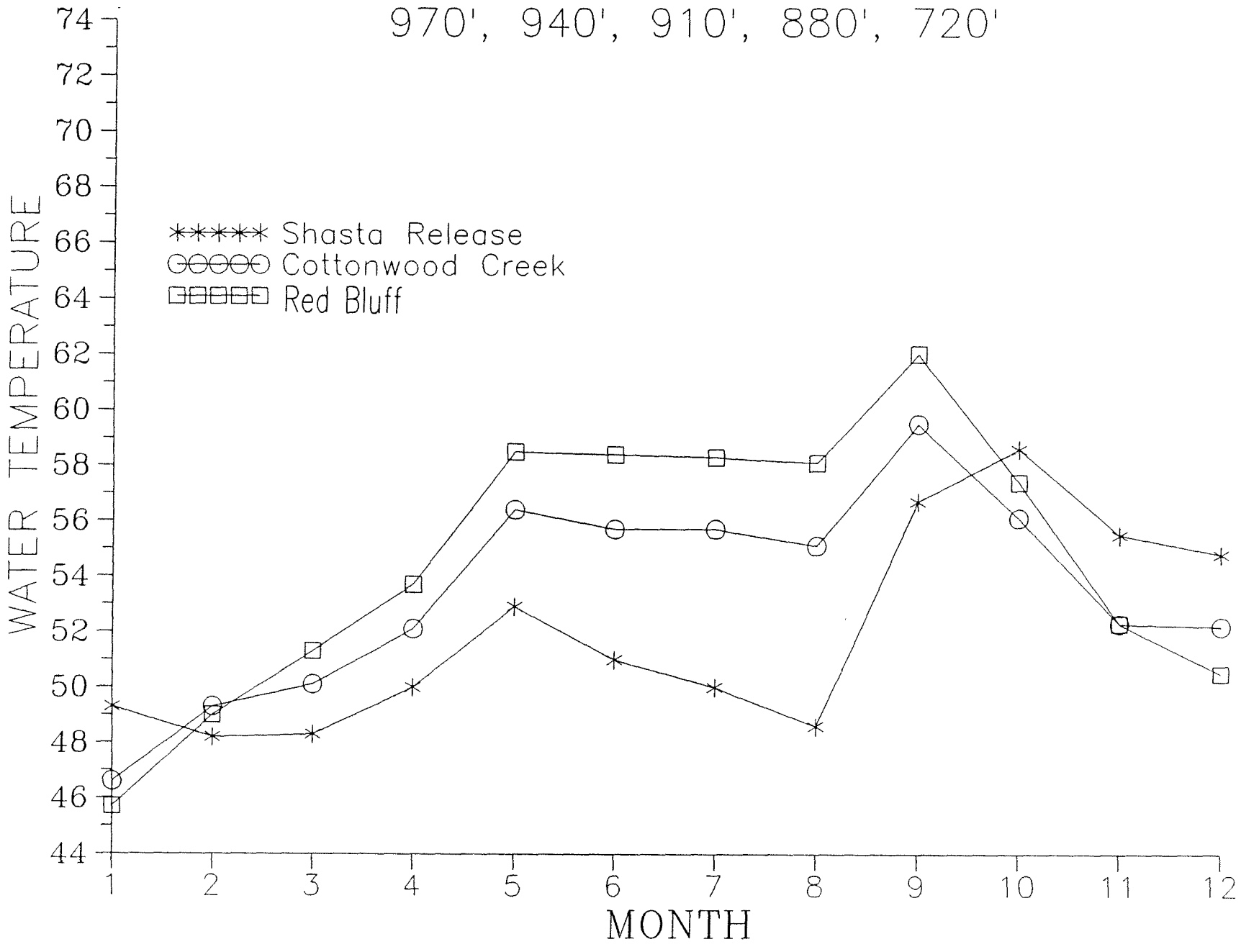

950 JAN-JUNE, 815 JULY-DEC
WATER TEMPERATURE
74
72
70
68
66
64
62
60
58
56
54
52
50
48
46
44
Shasta Release
Cottonwood Creek
Red Bluff
1
2
3
4
5
6
7
8
9
10
11
12
MONTH

1966

970', 940', 910', 880', 750'



1988


970', 940', 910', 880', 720'
WATER TEMPERATURE
74
72
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44
Shasta Release
Cottonwood Creek
Red Bluff
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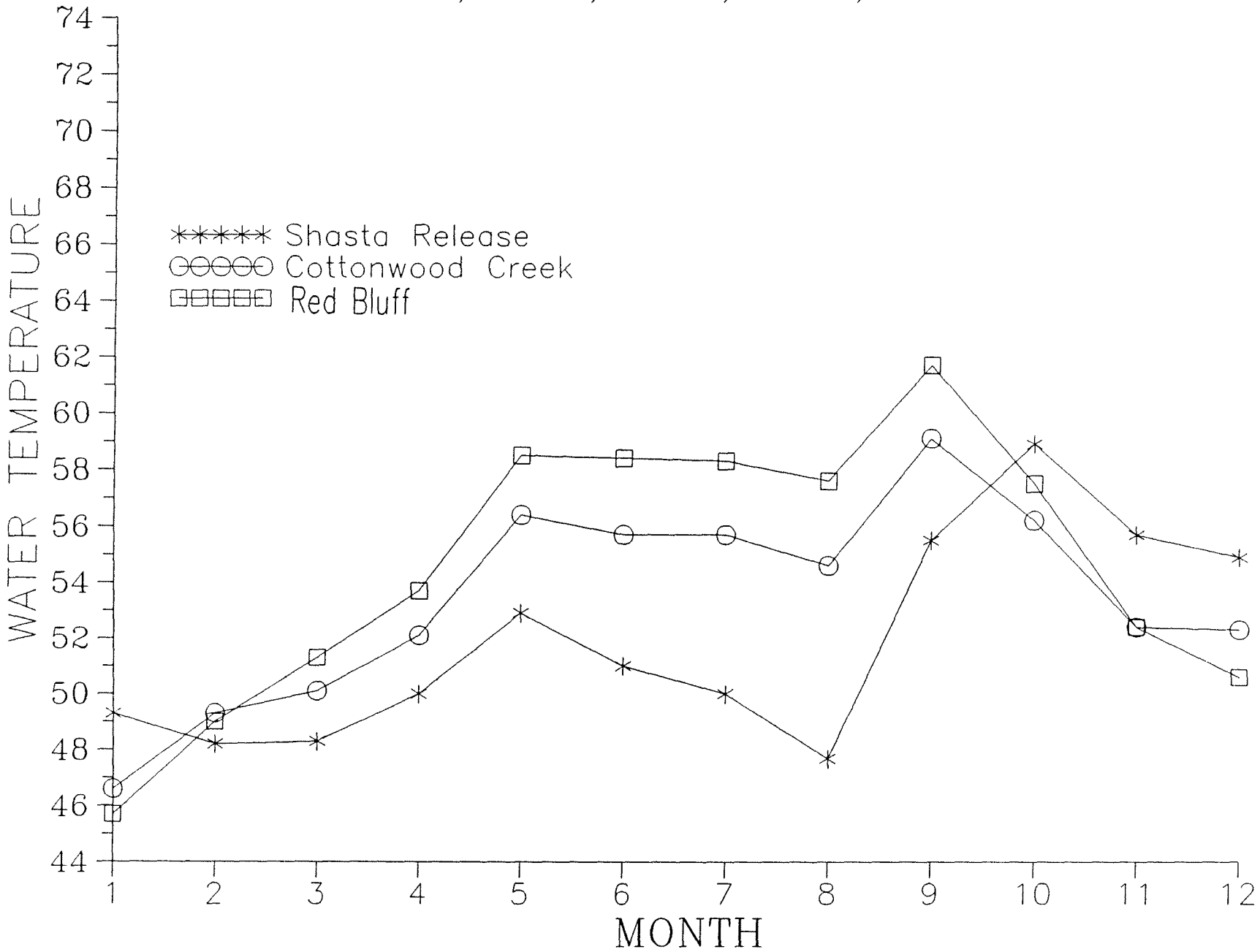
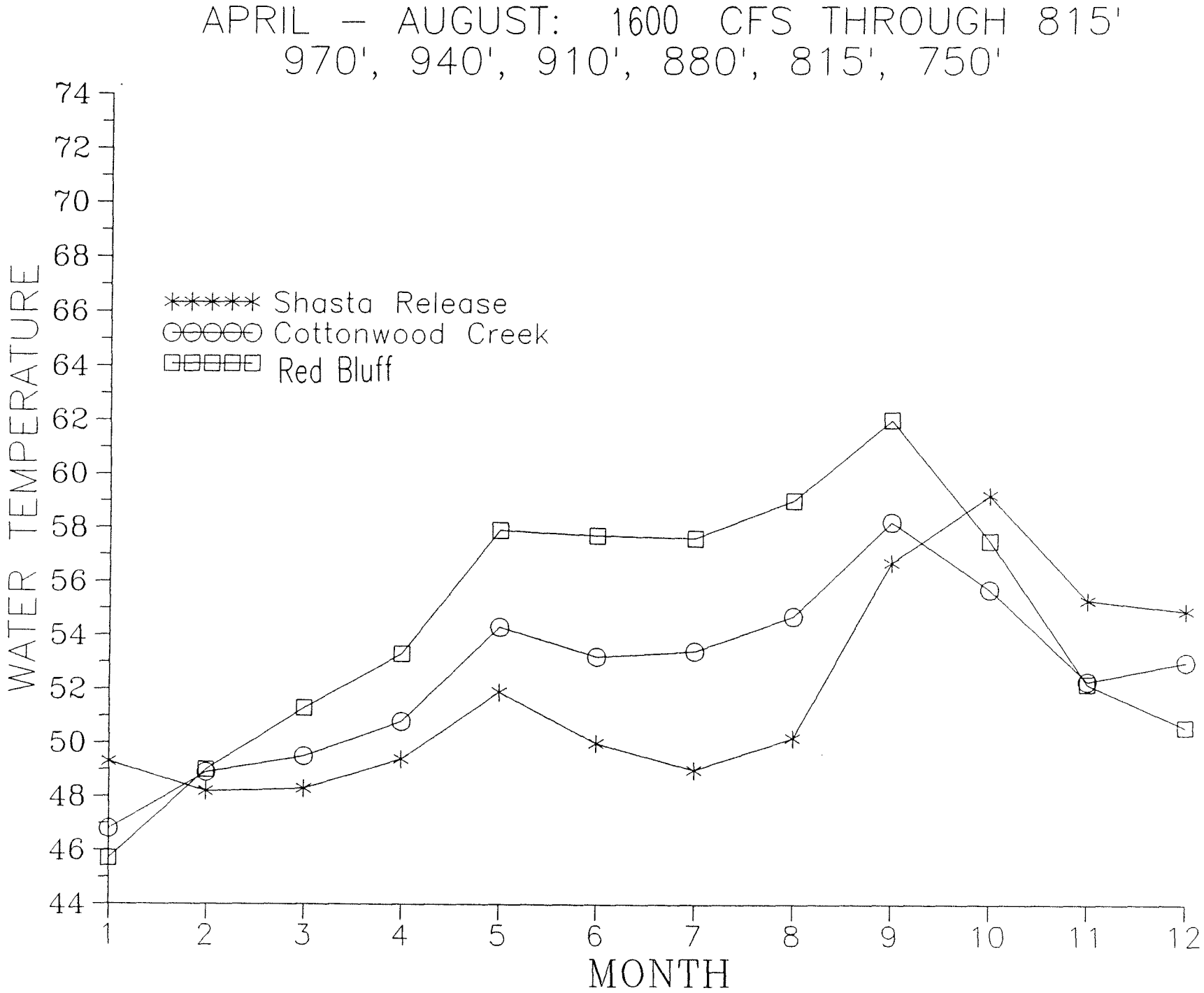
MONTH

1988

970', 940', 910', 880', 650'




APRIL – AUGUST: 1600 CFS THROUGH 815'
970', 940', 910', 880', 815', 750'
WATER TEMPERATURE
74
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Shasta Release
Cottonwood Creek
Red Bluff
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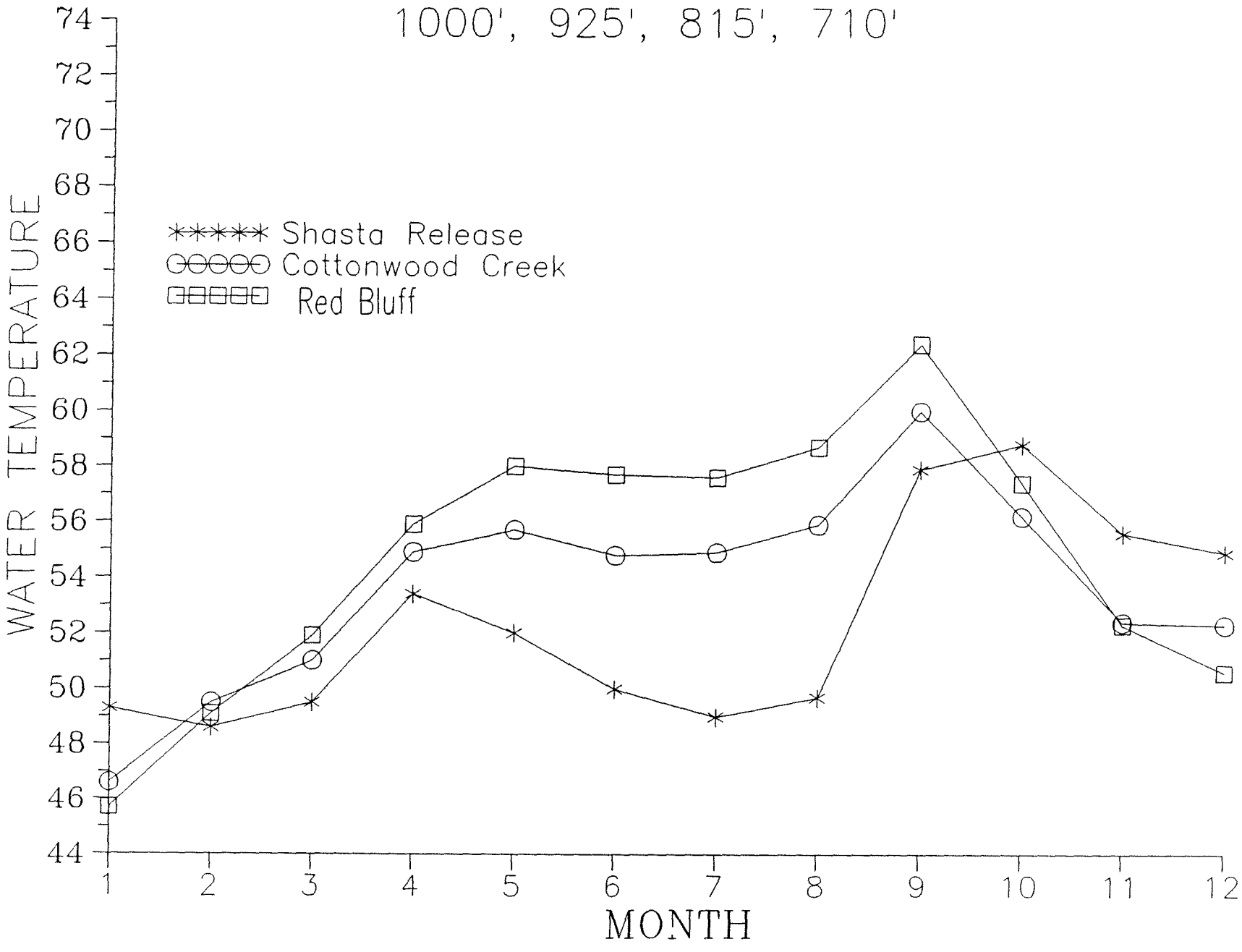
MONTH

1988


1000', 925', 815', 710'
WATER TEMPERATURE
74
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Shasta Release
Cottonwood Creek
Red Bluff
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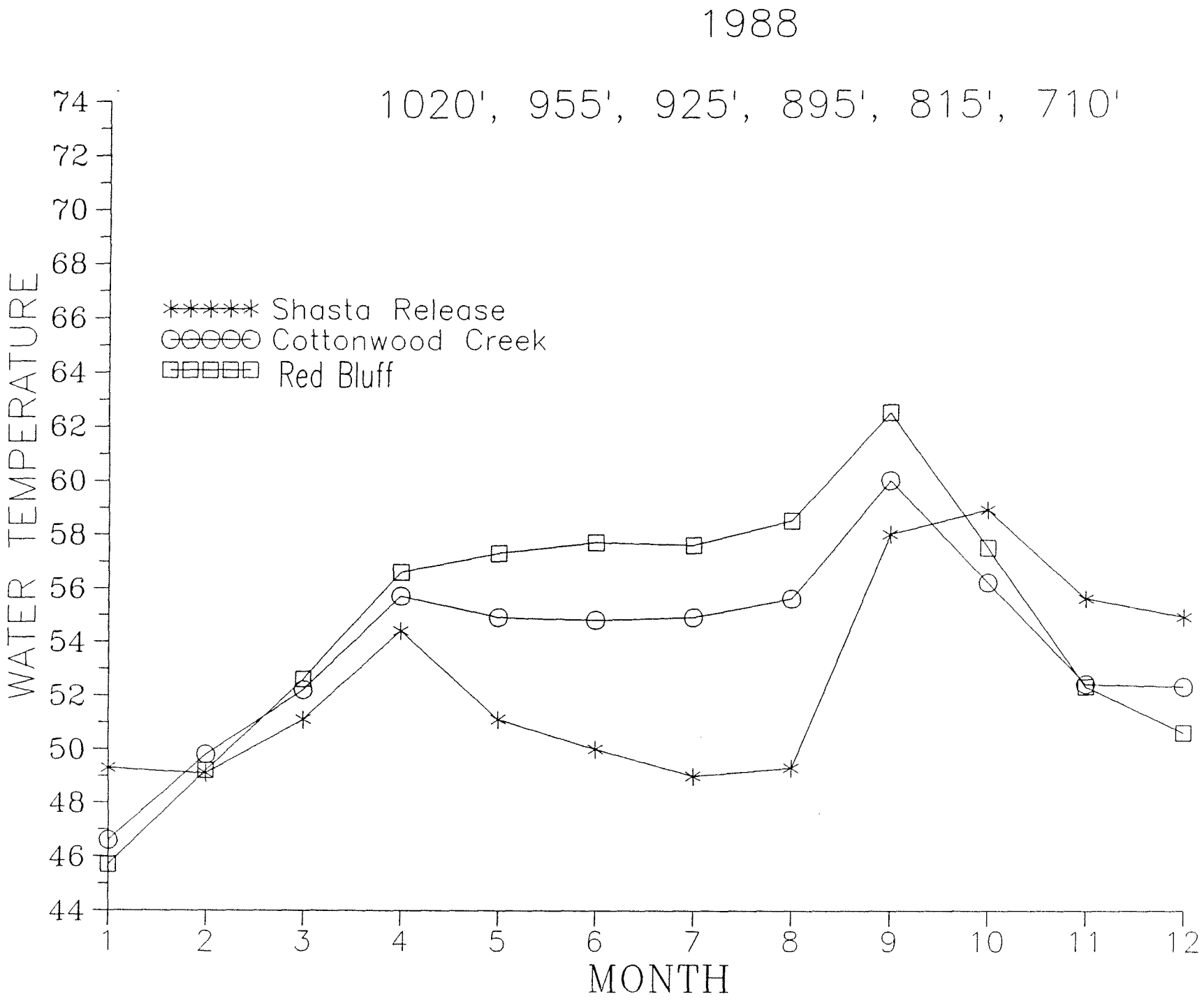
MONTH


1988
1020', 955', 925', 895', 815', 710'
WATER TEMPERATURE
74
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***** Shasta Release
Cottonwood Creek
Red Bluff
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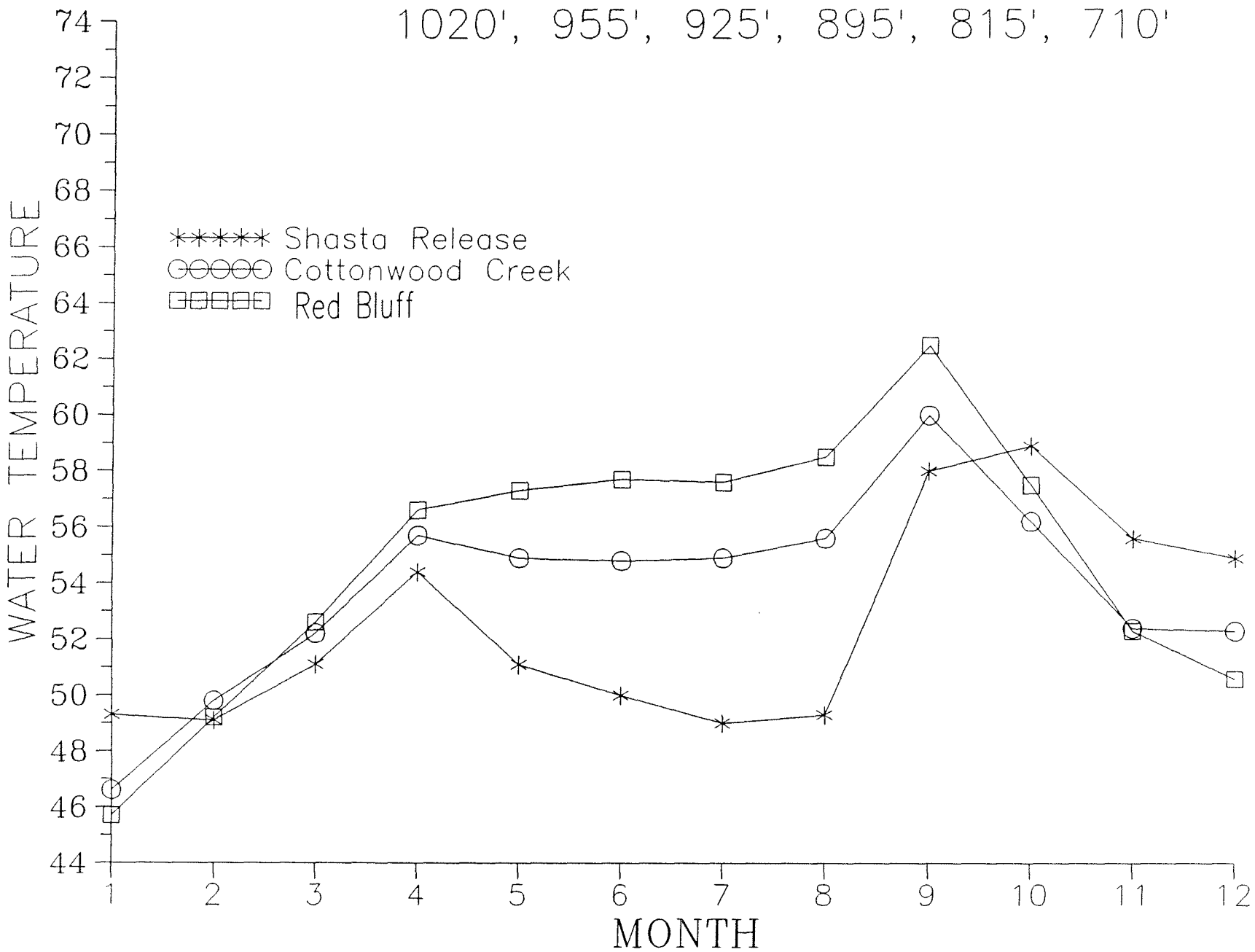
MONTH

1988


1020', 955', 925', 895', 815', 710'
Shasta Release
Cottonwood Creek
Red Bluff
WATER TEMPERATURE
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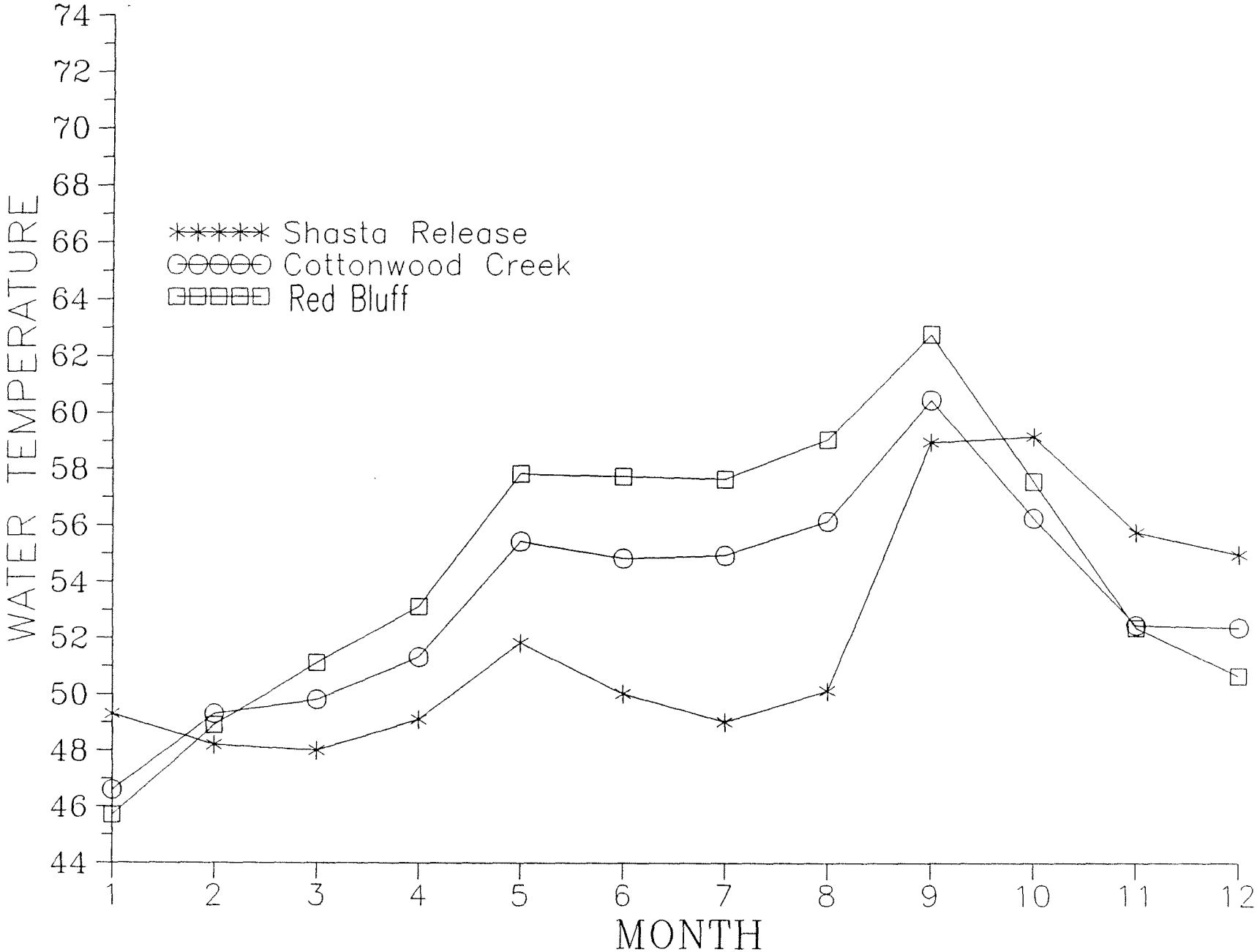
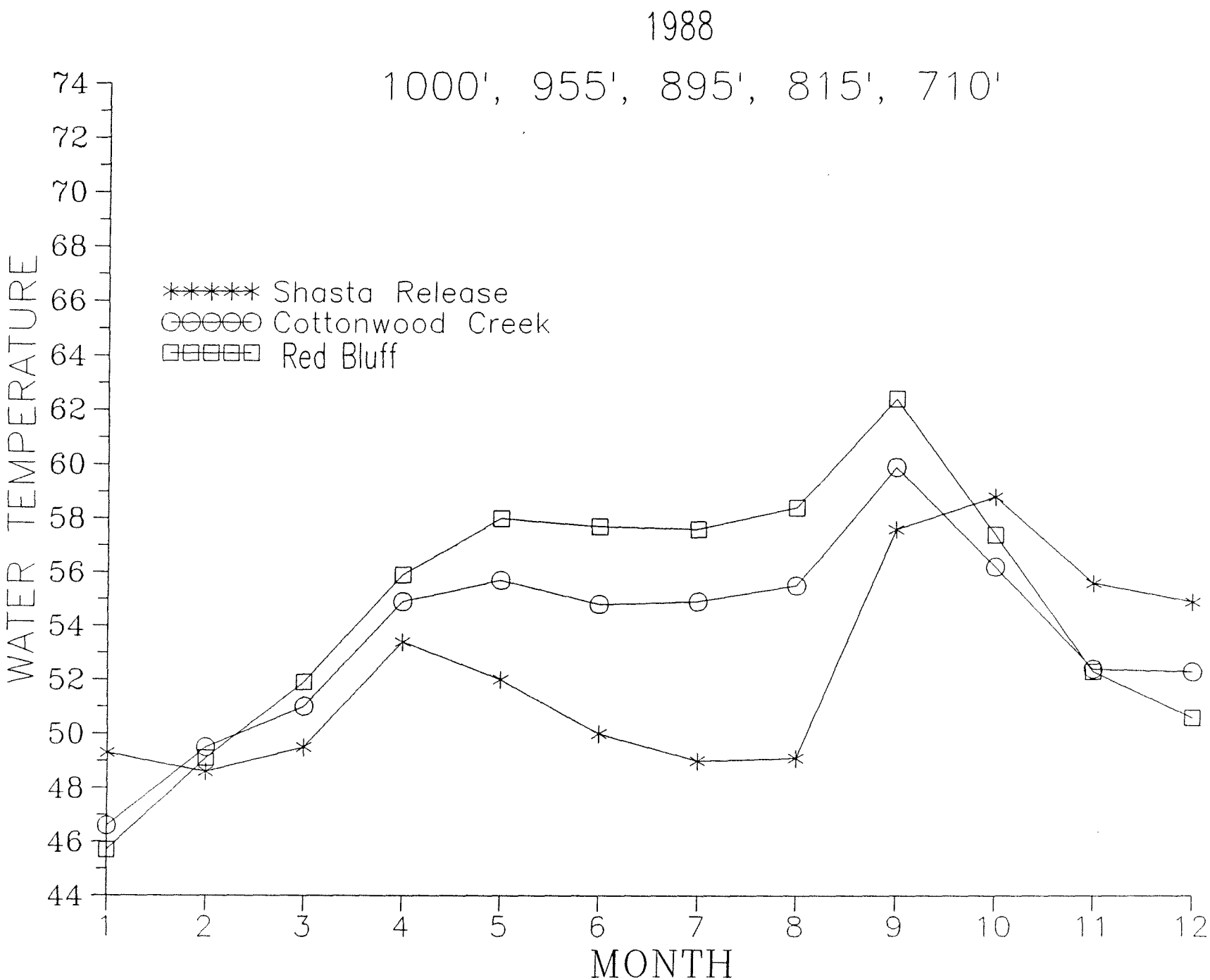
MONTH

1988

1045', 955', 925', 895', 815', 710'



A-13


1988
1000', 955', 895', 815', 710'
WATER TEMPERATURE
MONTH
Shasta Release
Cottonwood Creek
Red Bluff
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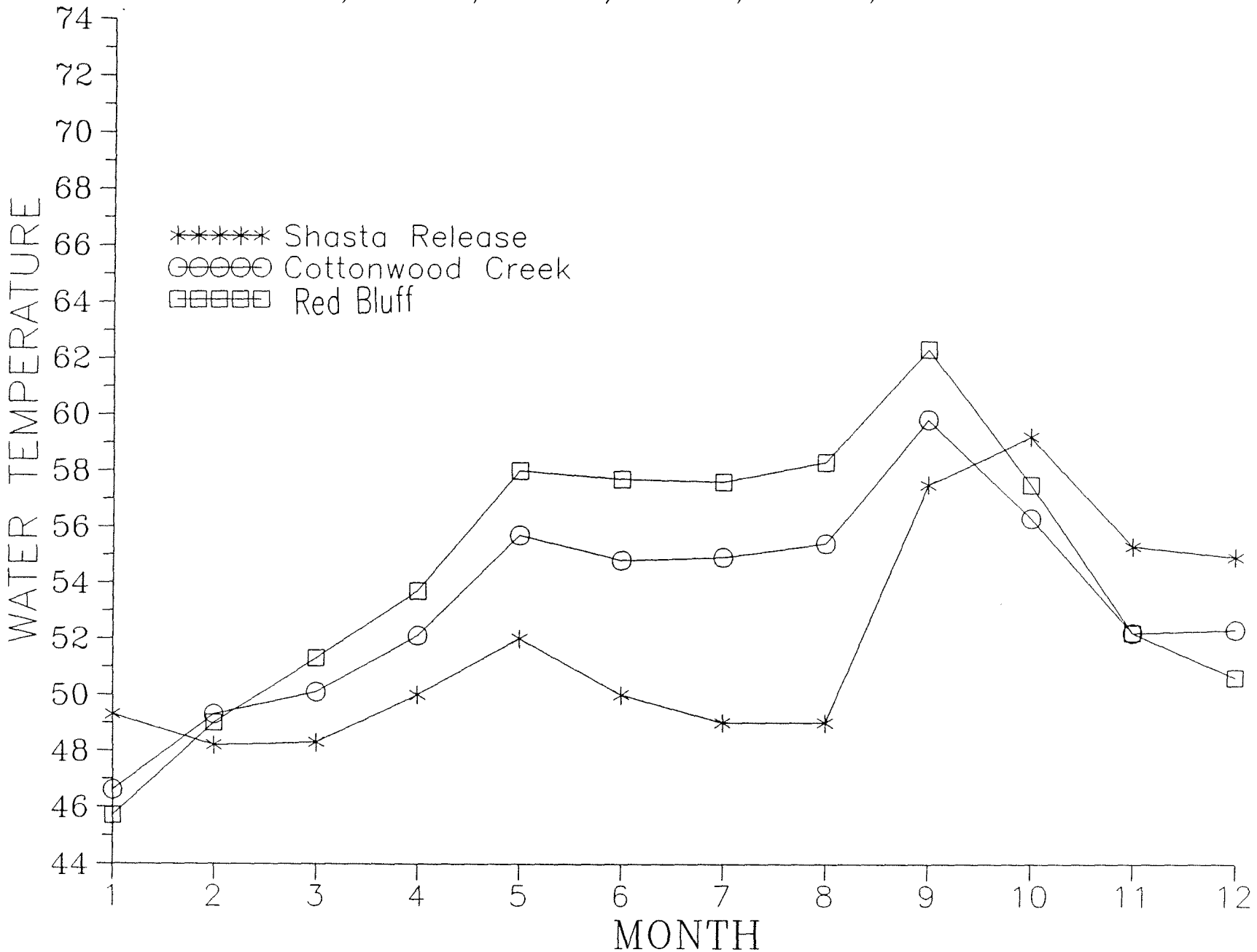
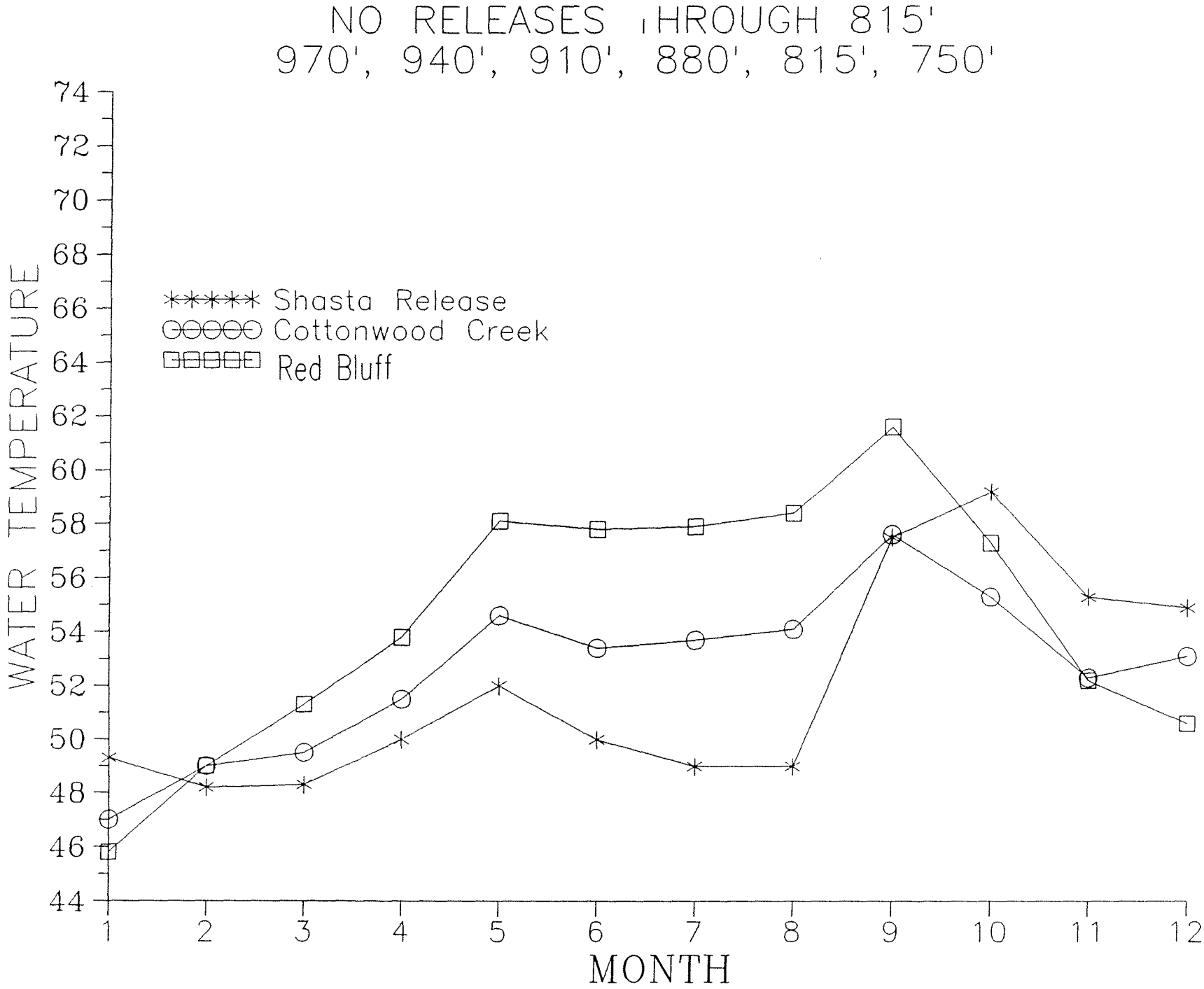
1988

970', 940', 910', 880', 815', 750'




NO RELEASES THROUGH 815'
970', 940', 910', 880', 815', 750'
WATER TEMPERATURE
74
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Shasta Release
Cottonwood Creek
Red Bluff
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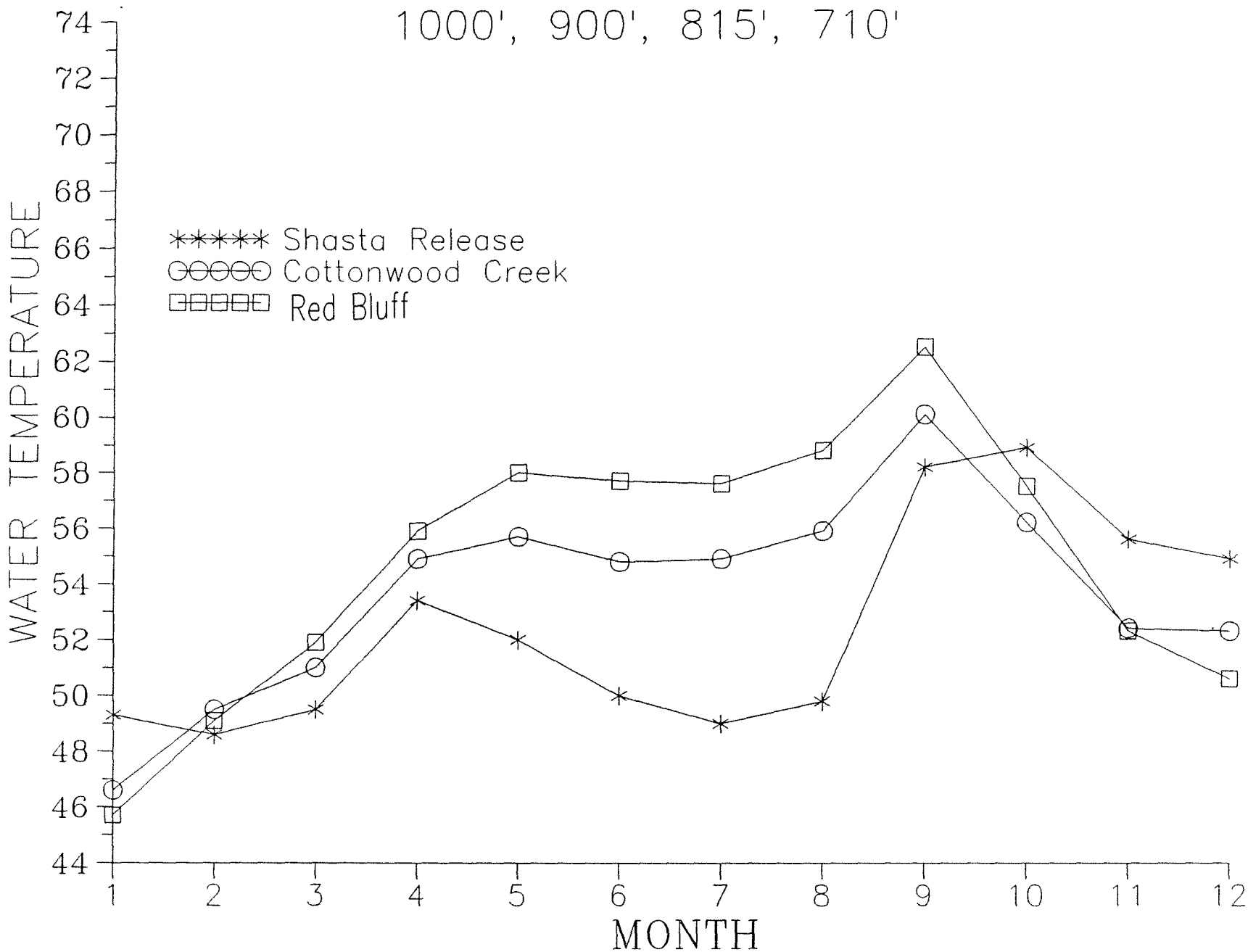
MONTH

1988


1000', 900', 815', 710'
WATER TEMPERATURE
74
72
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Shasta Release
Cottonwood Creek
Red Bluff
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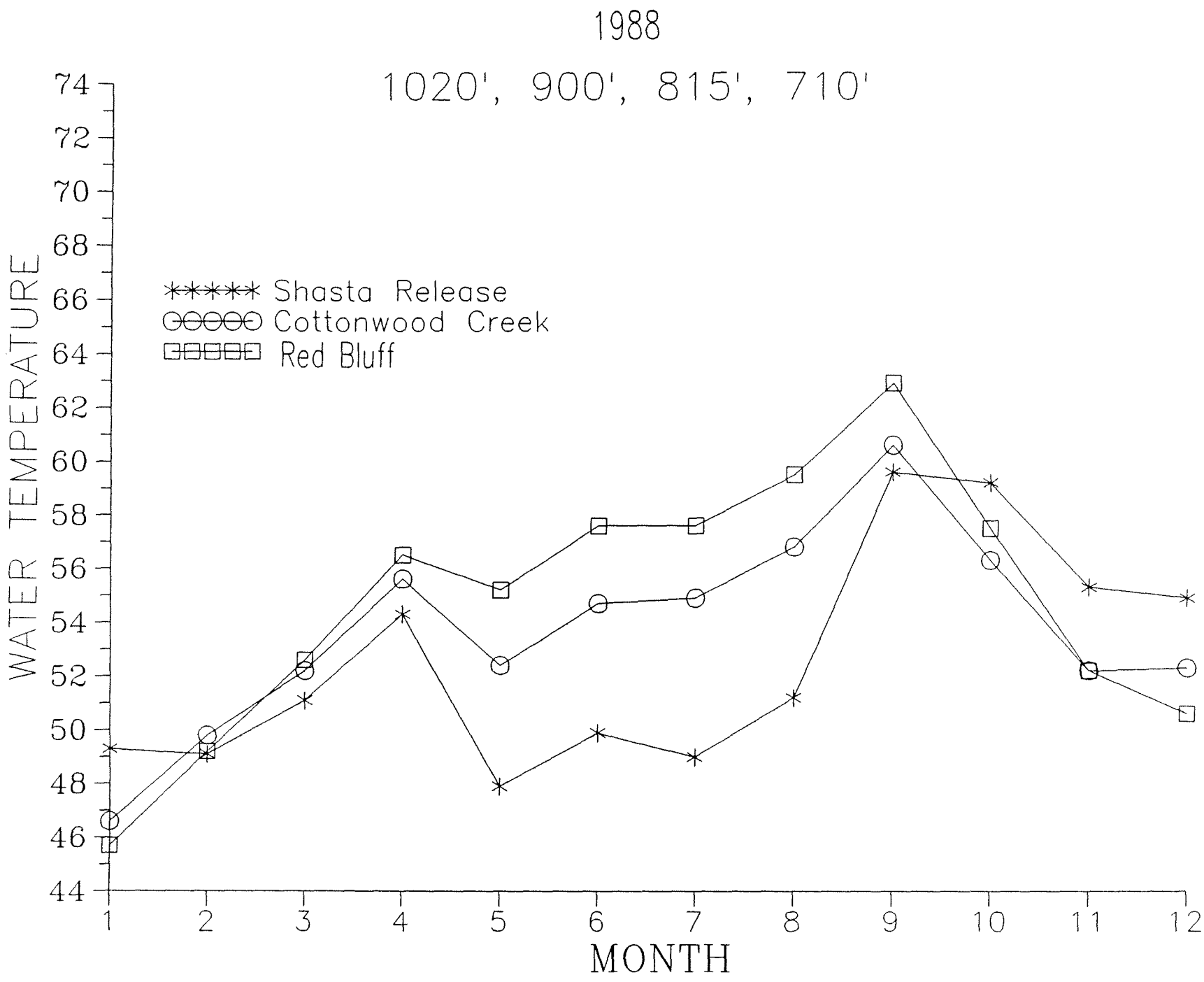
MONTH


1988
1020', 900', 815', 710'
WATER TEMPERATURE
74
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***** Shasta Release
Cottonwood Creek
Red Bluff
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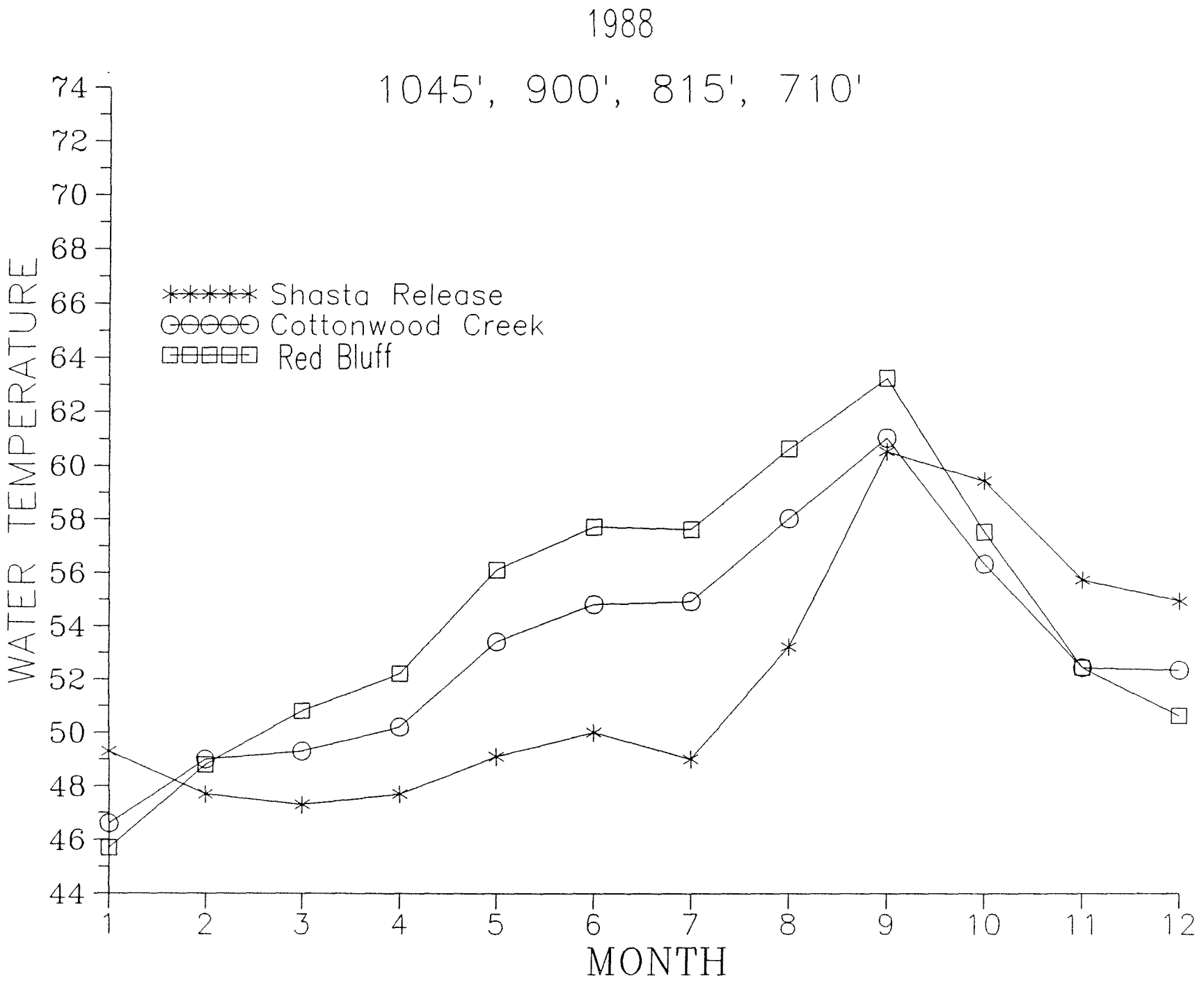
MONTH


1988
1045', 900', 815', 710'
WATER TEMPERATURE
74
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***** Shasta Release
Cottonwood Creek
Red Bluff
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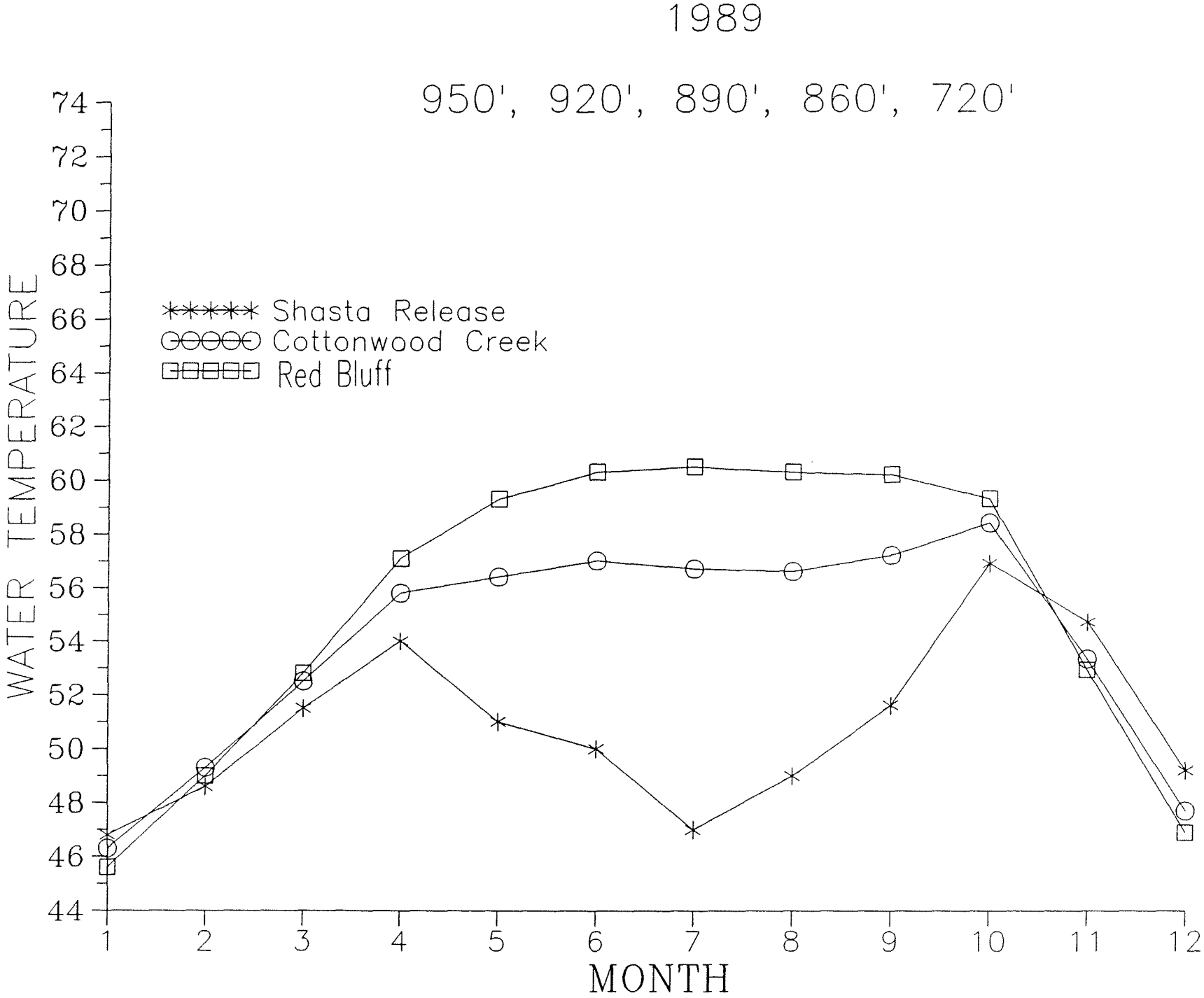
MONTH


1989
950', 920', 890', 860', 720'
WATER TEMPERATURE
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***** Shasta Release
Cottonwood Creek
Red Bluff
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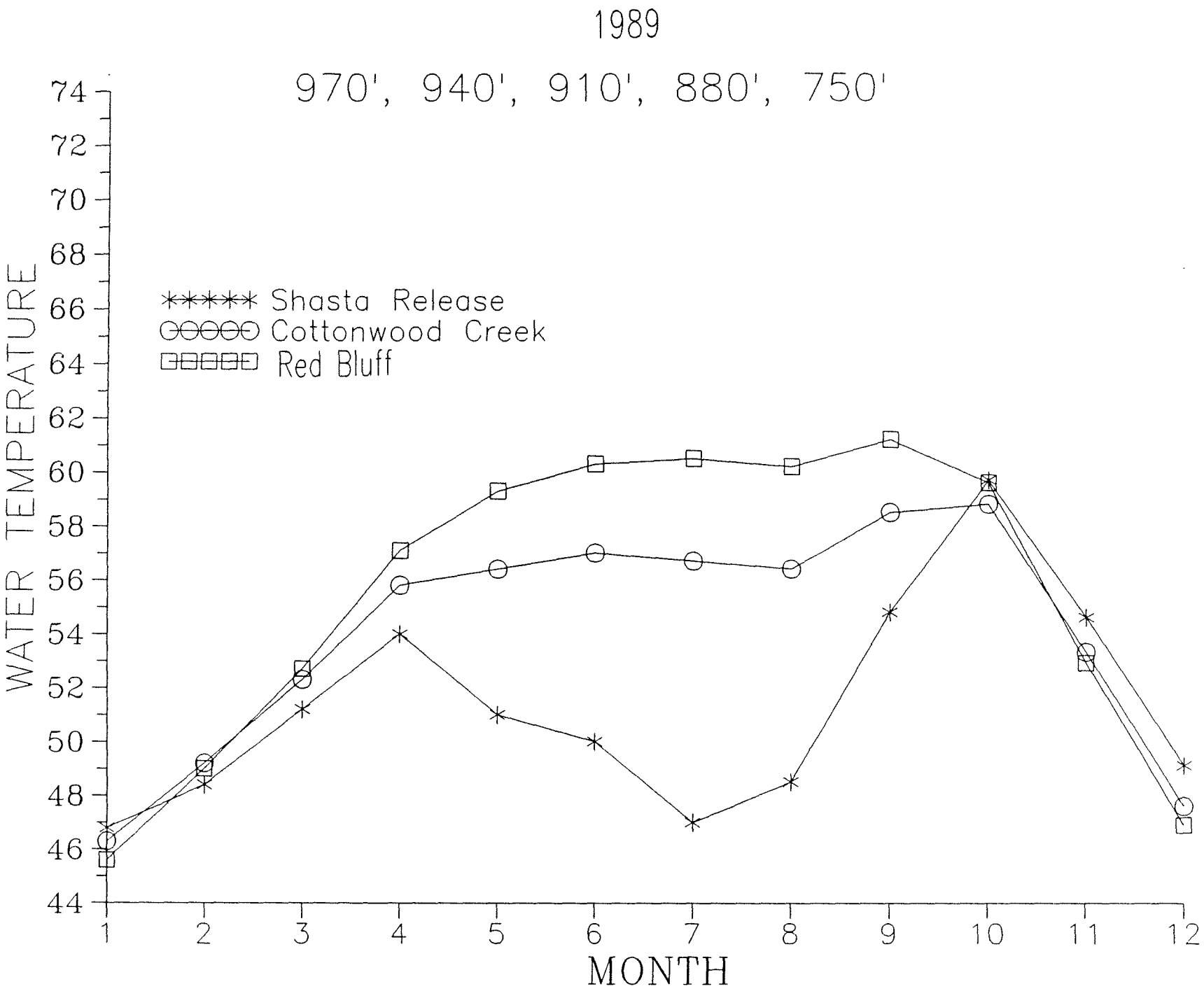
MONTH


1989
970', 940', 910', 880', 750'
WATER TEMPERATURE
74
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***** Shasta Release
Cottonwood Creek
Red Bluff
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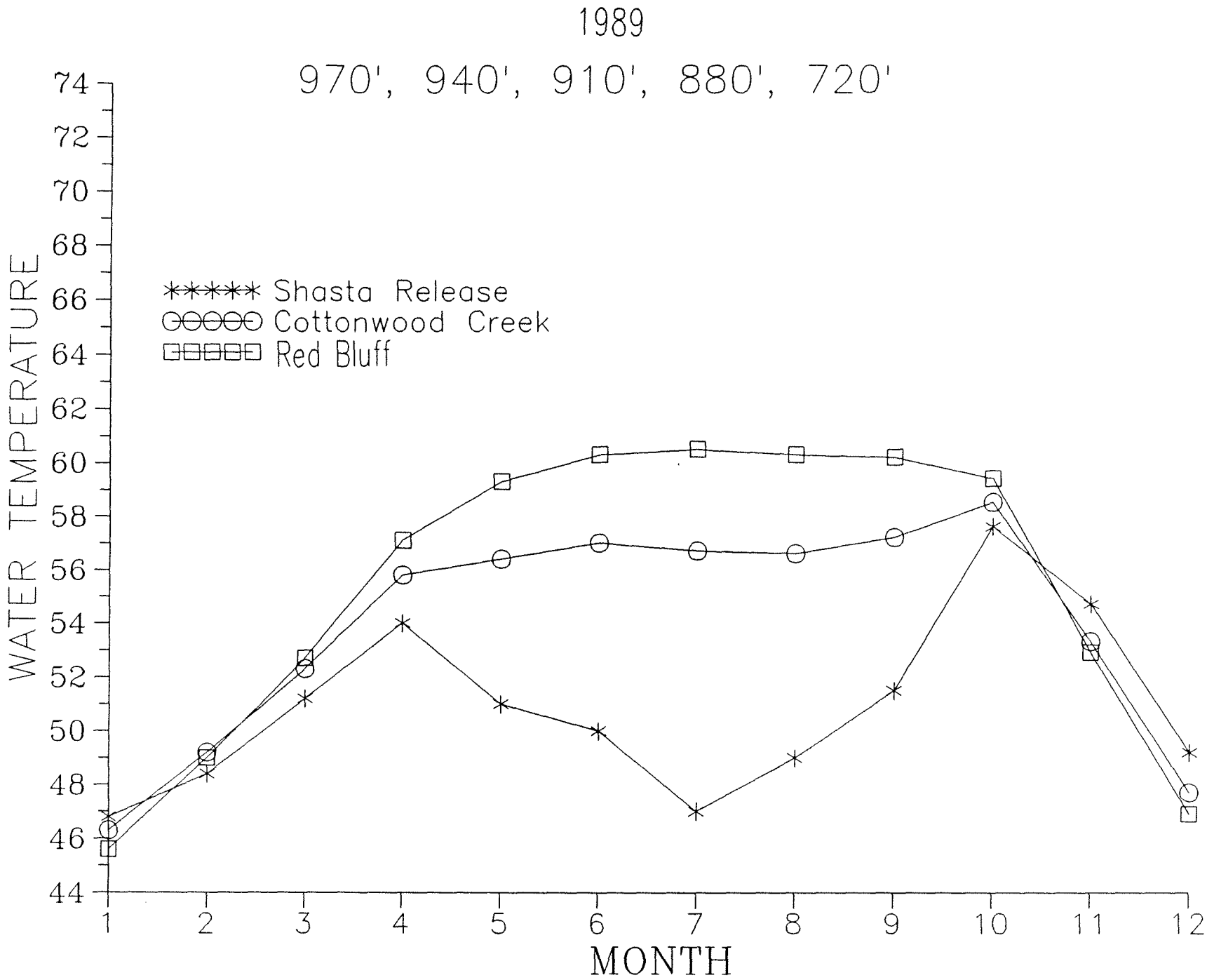
MONTH


1989
970', 940', 910', 880', 720'
WATER TEMPERATURE
74
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Shasta Release
Cottonwood Creek
Red Bluff
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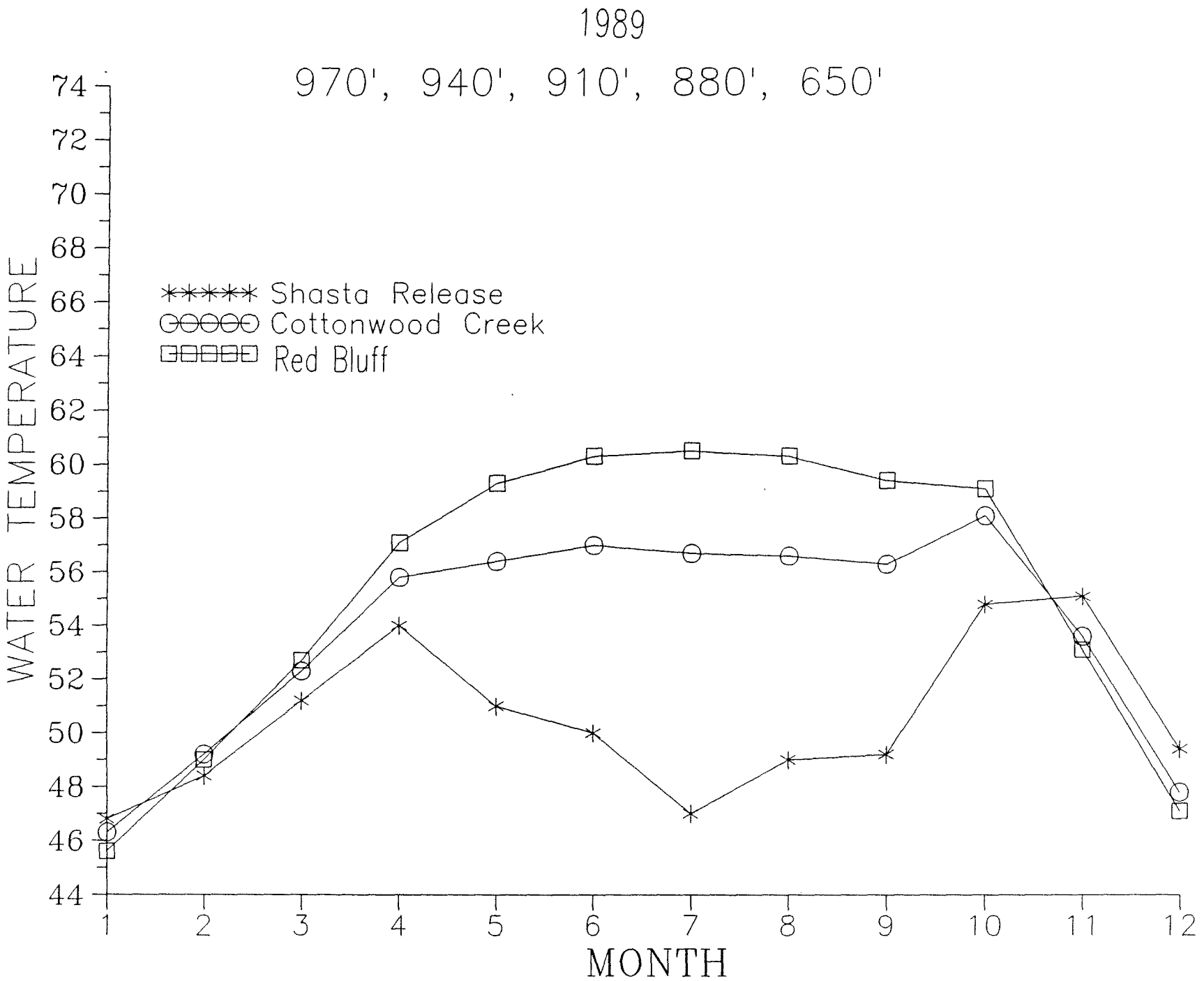
MONTH


1989
970', 940', 910', 880', 650'
WATER TEMPERATURE
74
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***** Shasta Release
Cottonwood Creek
Red Bluff
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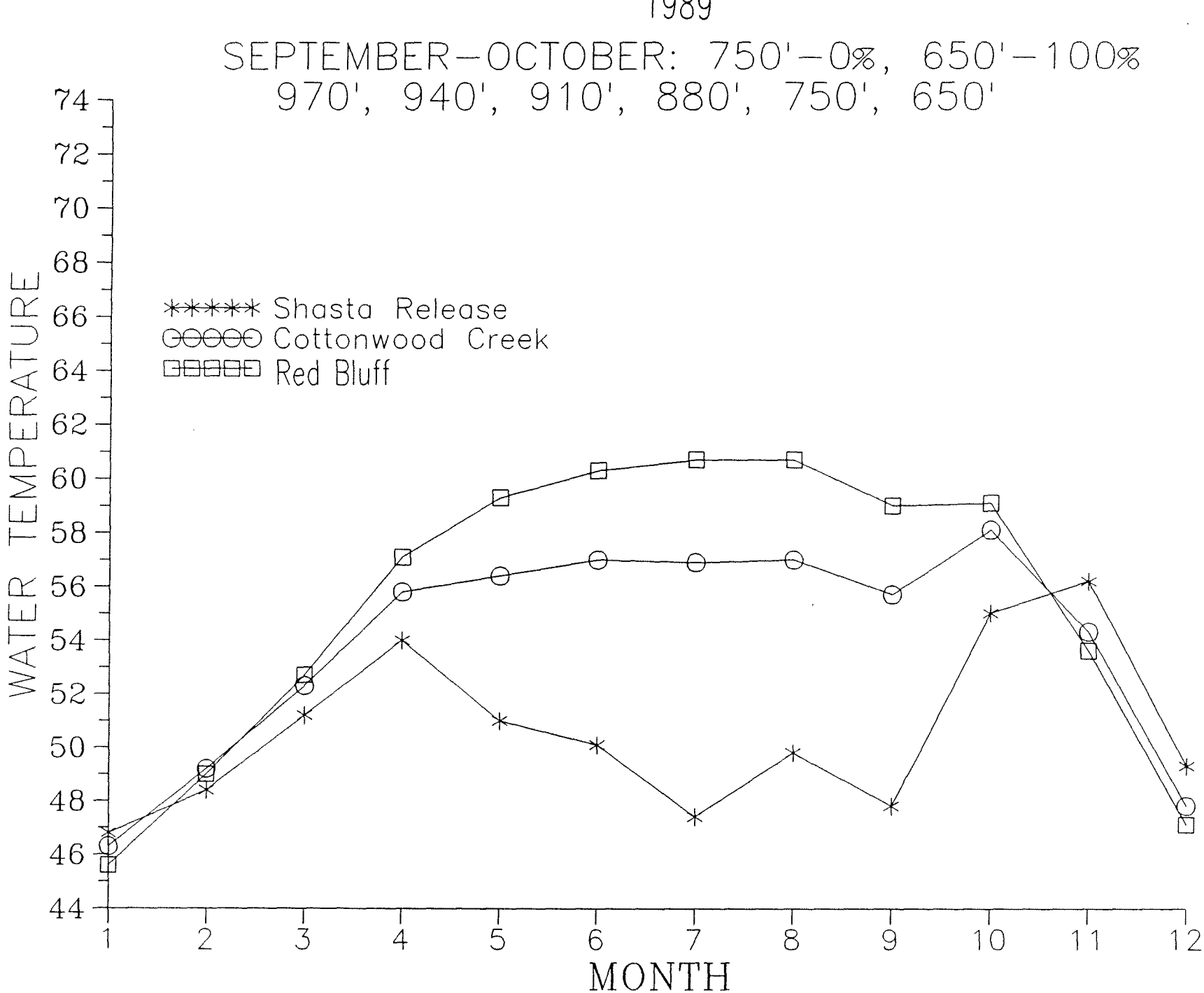
MONTH


1989
SEPTEMBER-OCTOBER: 750'-0%, 650'-100%
970', 940', 910', 880', 750', 650'
Shasta Release
Cottonwood Creek
Red Bluff
WATER TEMPERATURE
74
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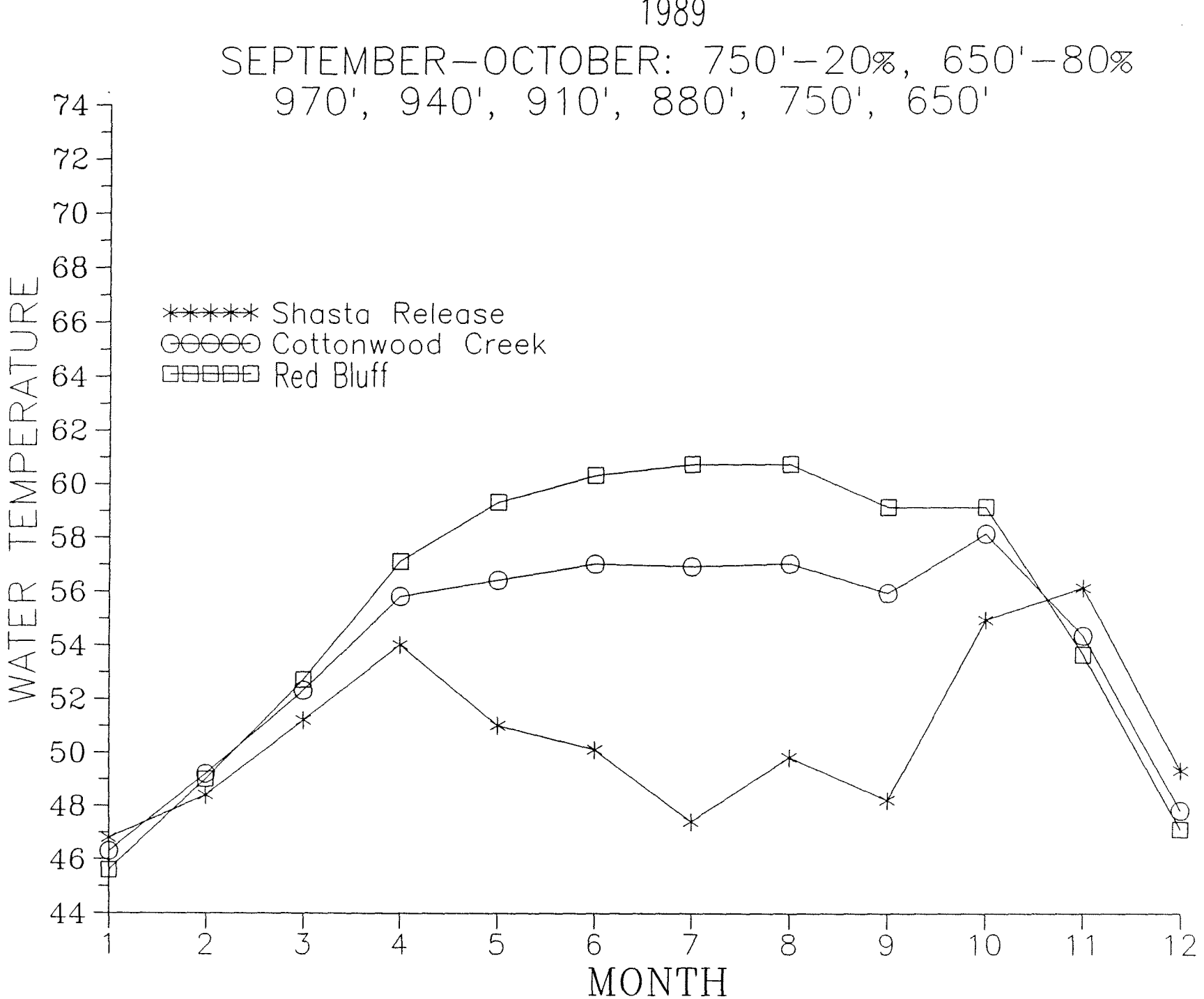
MONTH


1989
SEPTEMBER-OCTOBER: 750'-20%, 650'-80%
970', 940', 910', 880', 750', 650'
WATER TEMPERATURE
74
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Shasta Release
Cottonwood Creek
Red Bluff
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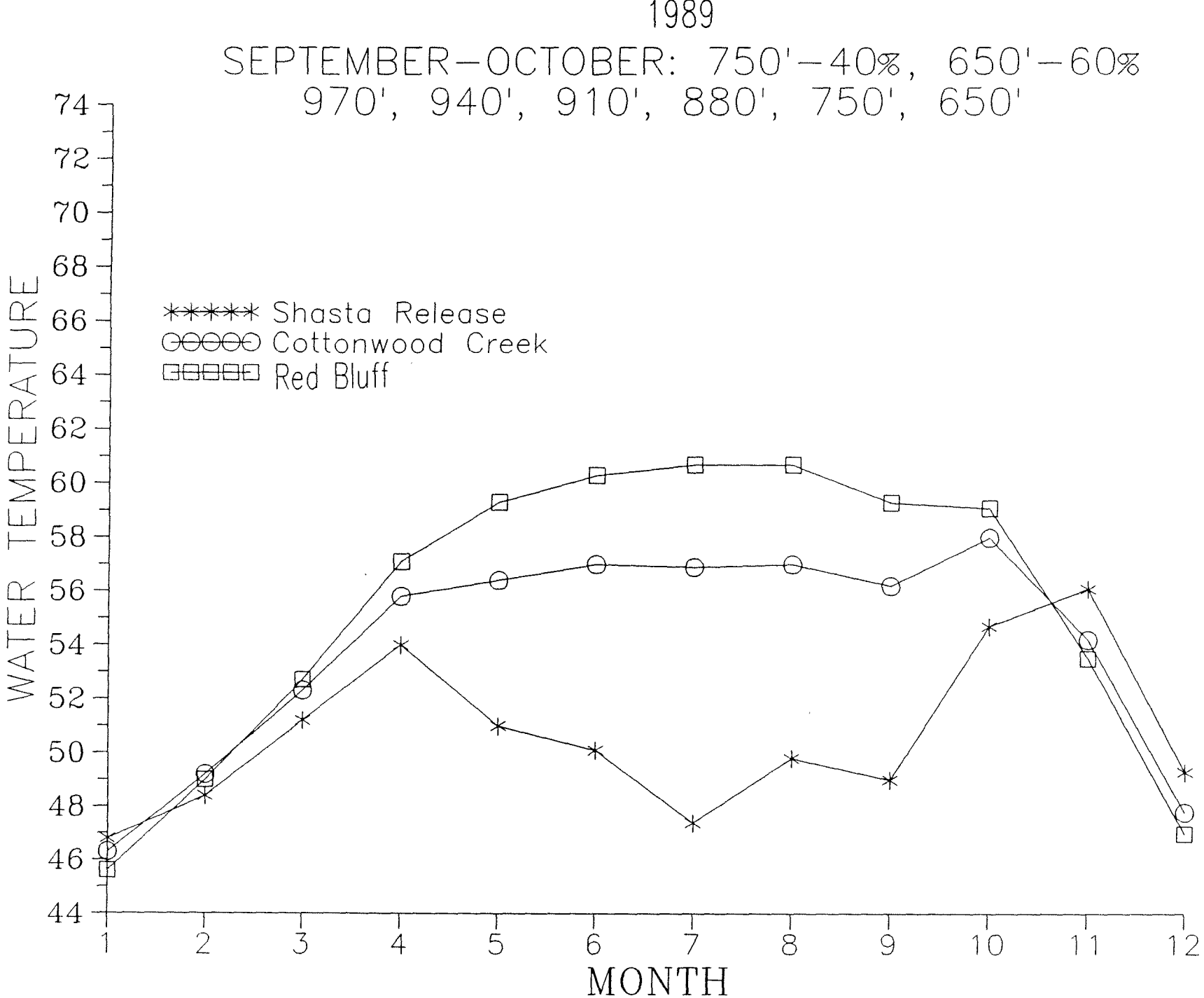
MONTH


1989
SEPTEMBER-OCTOBER: 750'-40%, 650'-60%
970', 940', 910', 880', 750', 650'
WATER TEMPERATURE
74
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***** Shasta Release
Cottonwood Creek
Red Bluff
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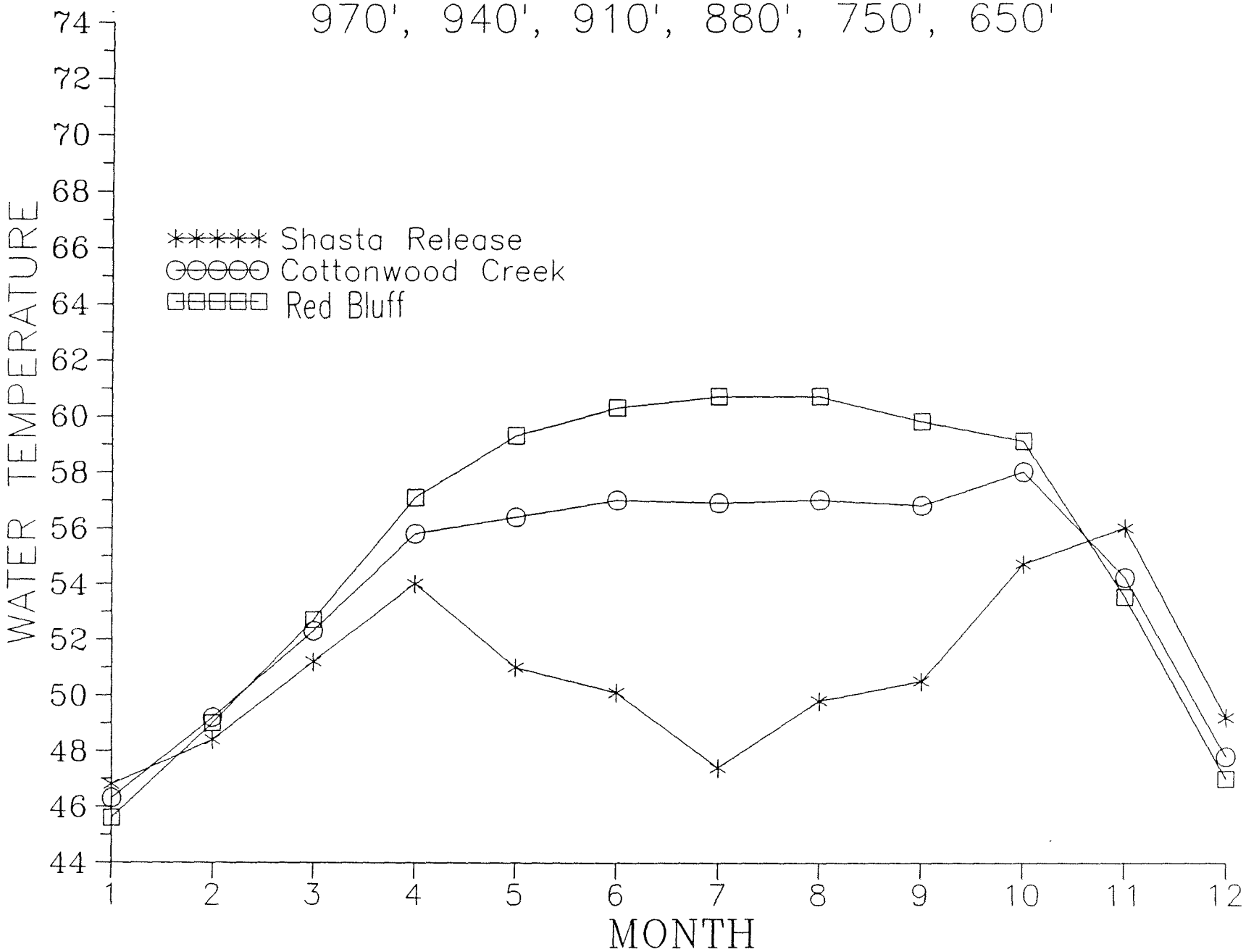
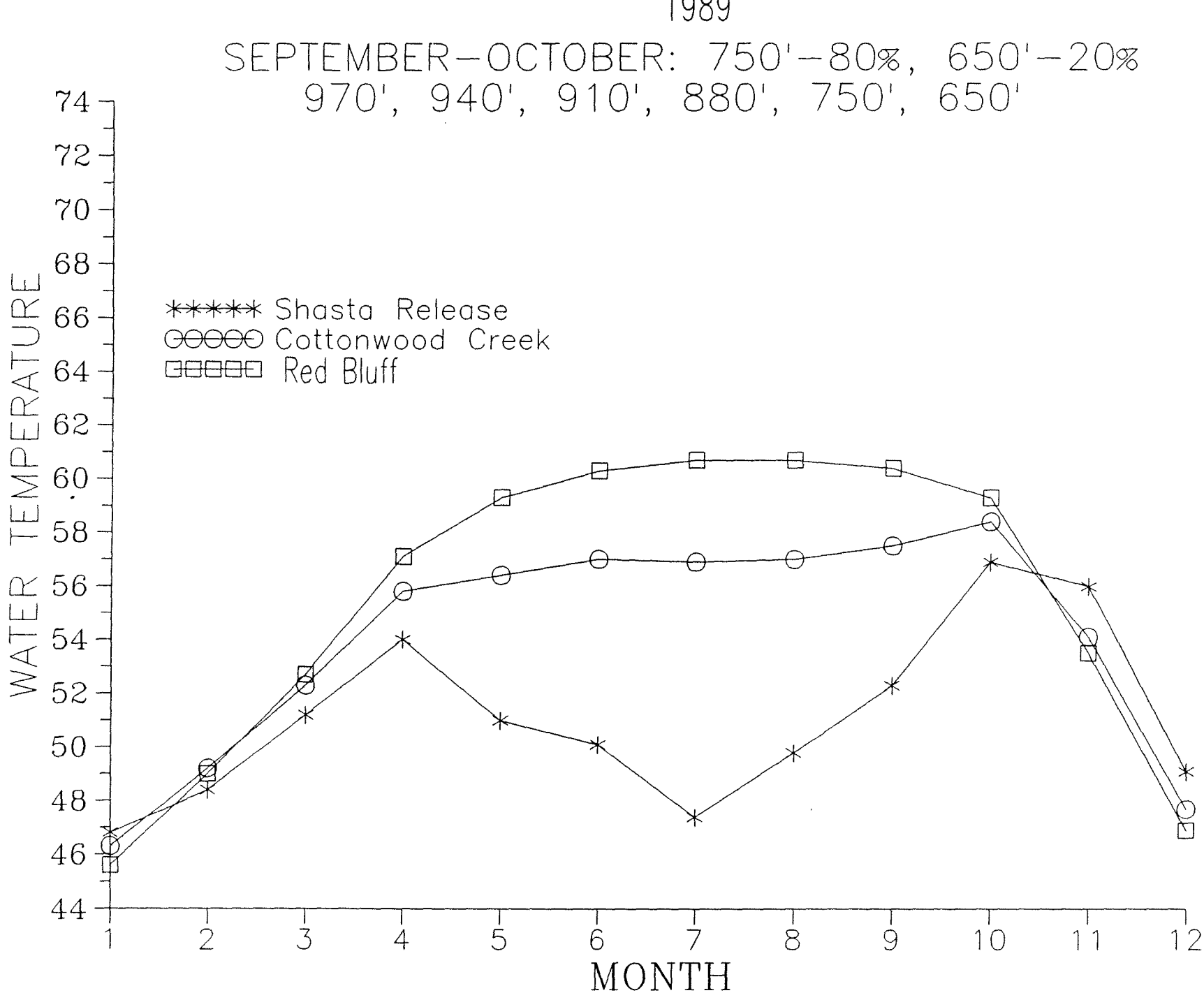
MONTH

1989

SEPTEMBER–OCTOBER: 750'–60%, 650'–40%
970', 940', 910', 880', 750', 650'




1989
SEPTEMBER-OCTOBER: 750'-80%, 650'-20%
970', 940', 910', 880', 750', 650'
WATER TEMPERATURE
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Shasta Release
Cottonwood Creek
Red Bluff
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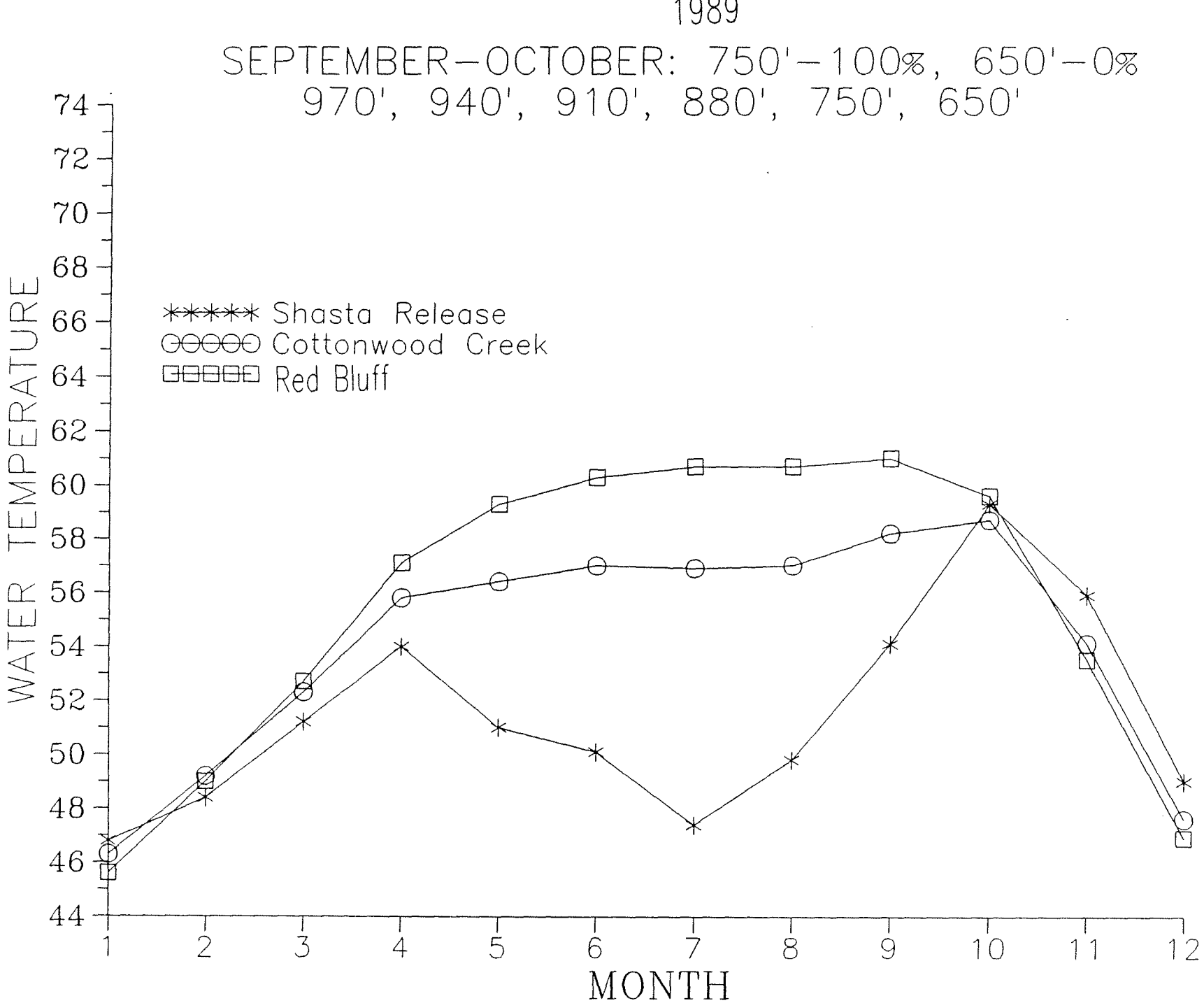
MONTH


1989
SEPTEMBER-OCTOBER: 750'-100%, 650'-0%
970', 940', 910', 880', 750', 650'
WATER TEMPERATURE
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***** Shasta Release
Cottonwood Creek
Red Bluff
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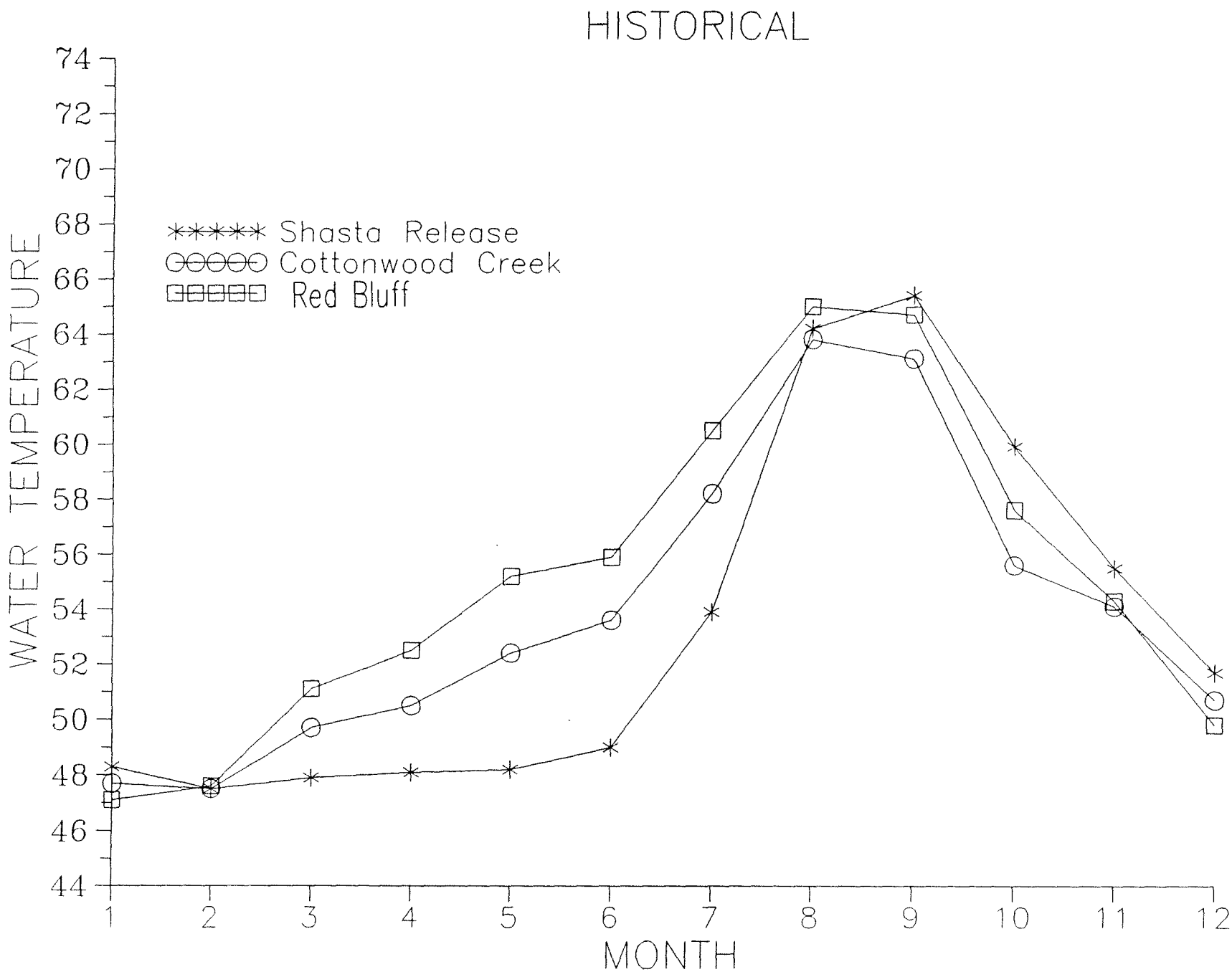
MONTH


HISTORICAL
Shasta Release
Cottonwood Creek
Red Bluff
WATER TEMPERATURE
74
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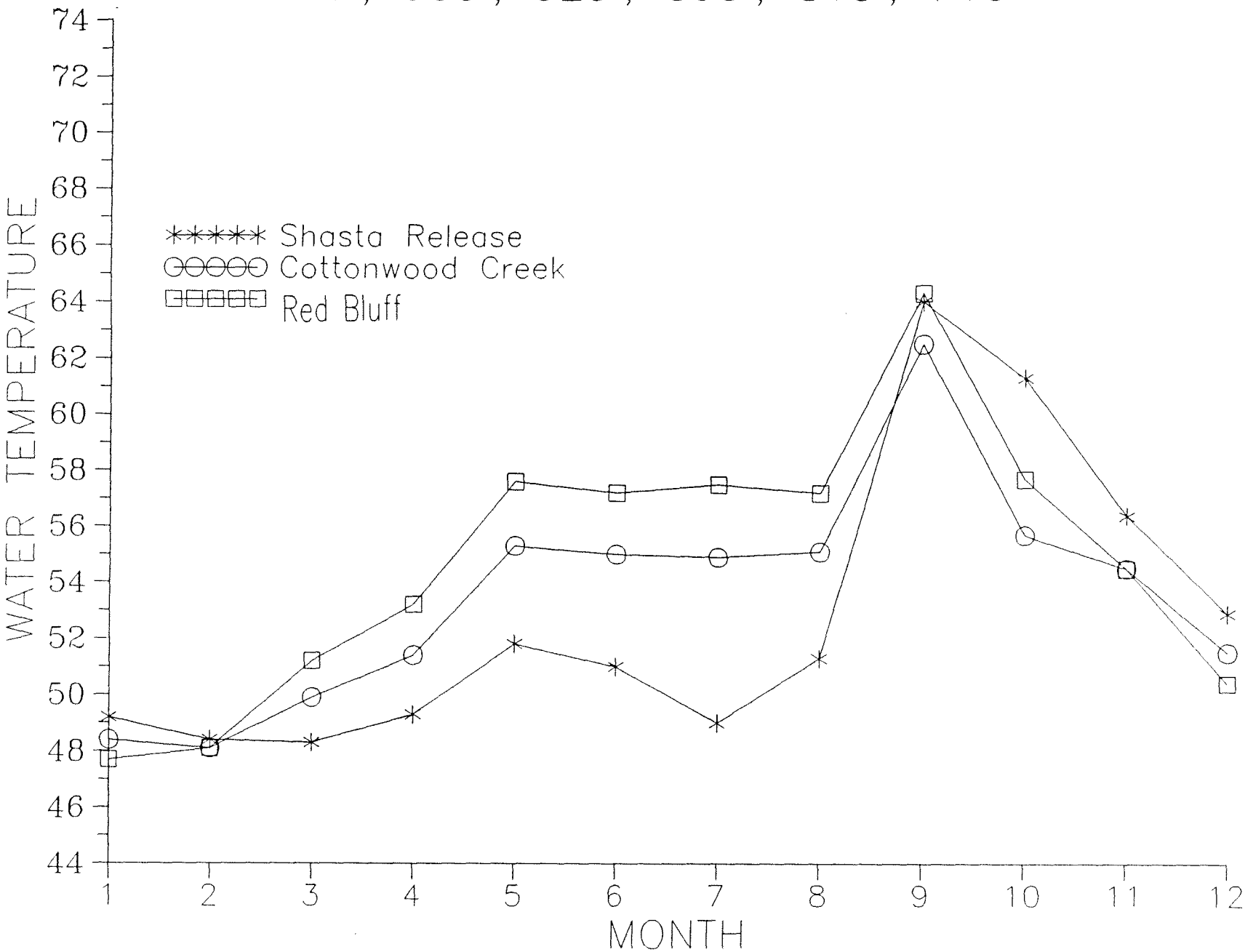
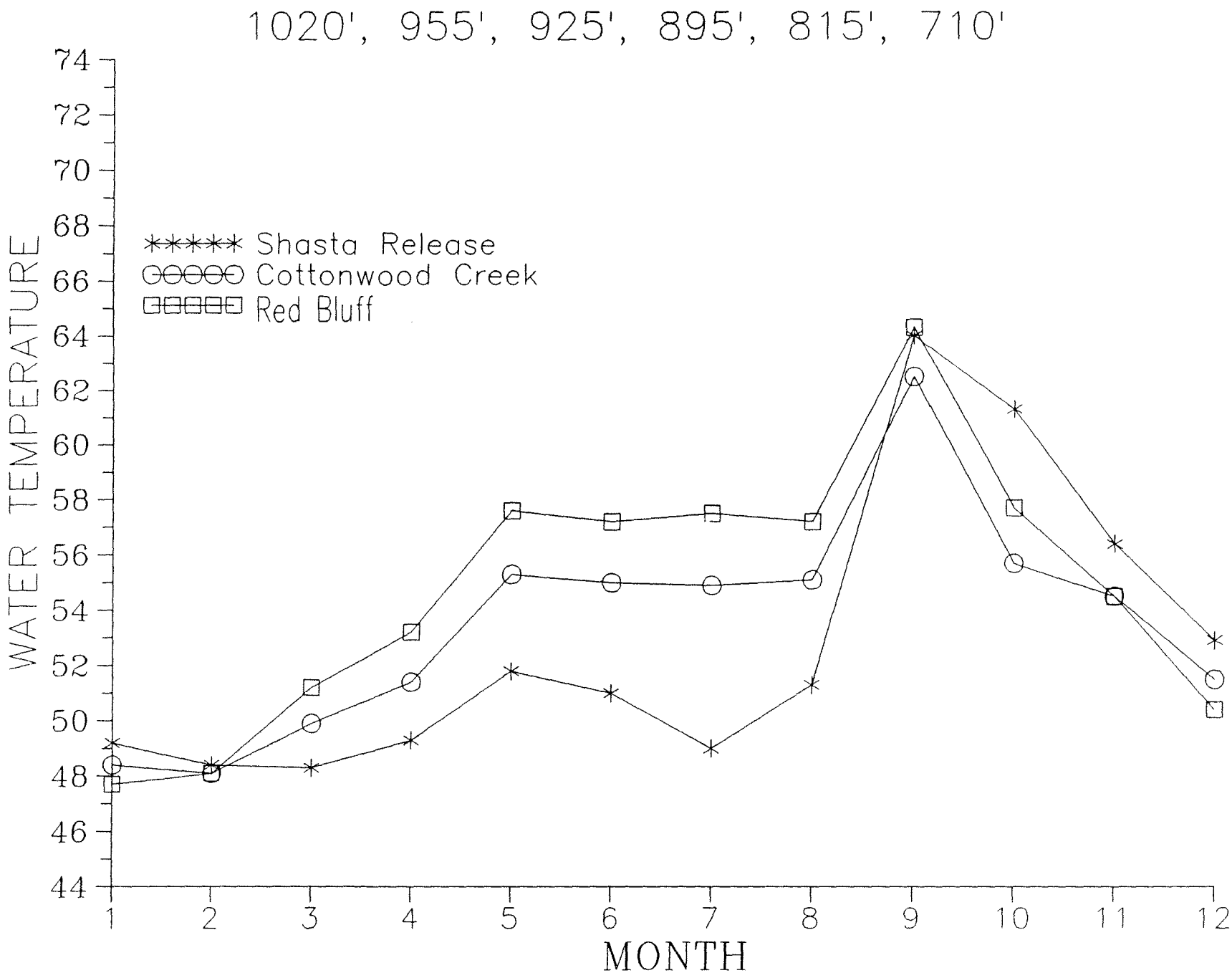
MONTH

1976

1045', 955', 925', 895', 815', 710'




1020', 955', 925', 895', 815', 710'
WATER TEMPERATURE
74
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44
Shasta Release
Cottonwood Creek
Red Bluff
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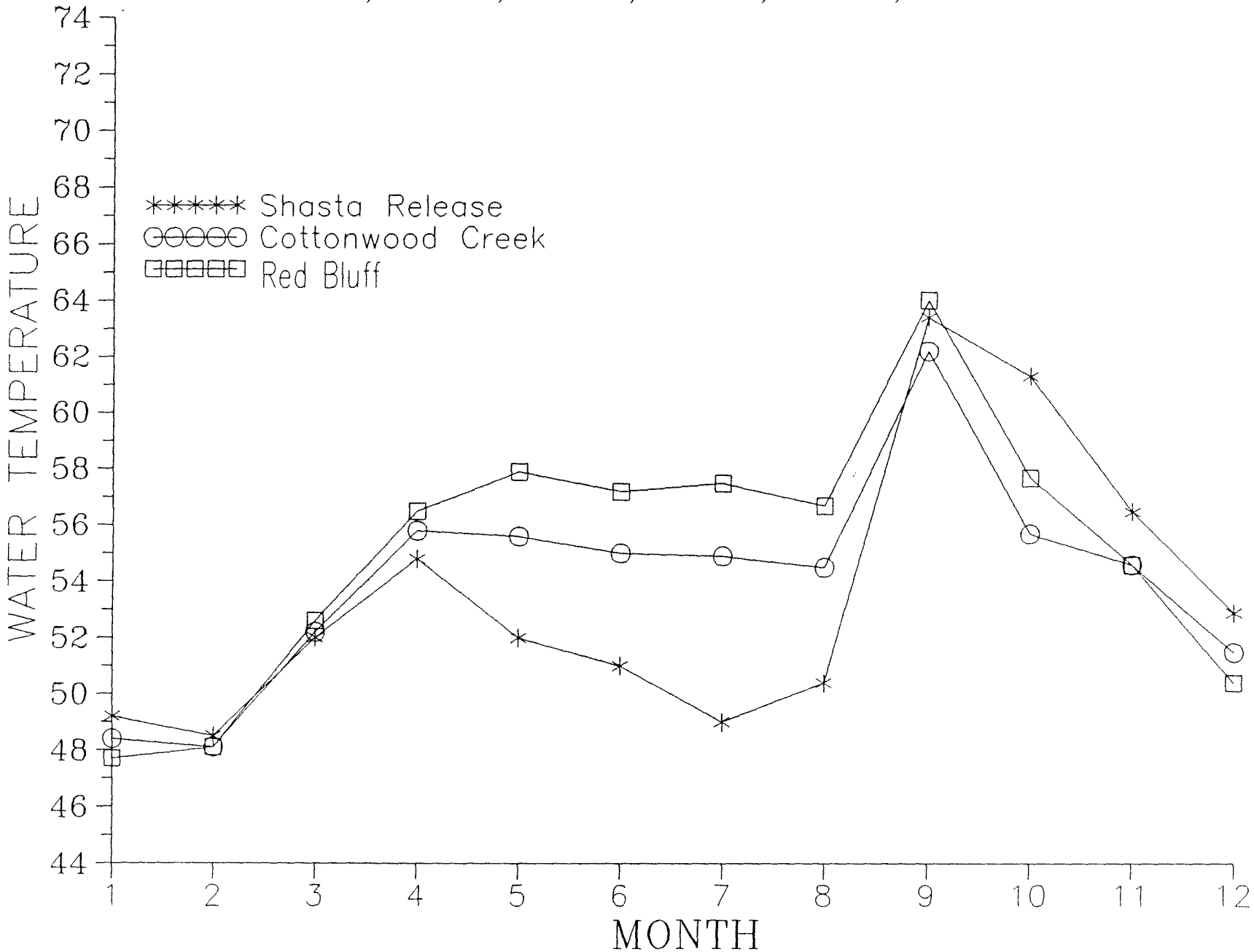
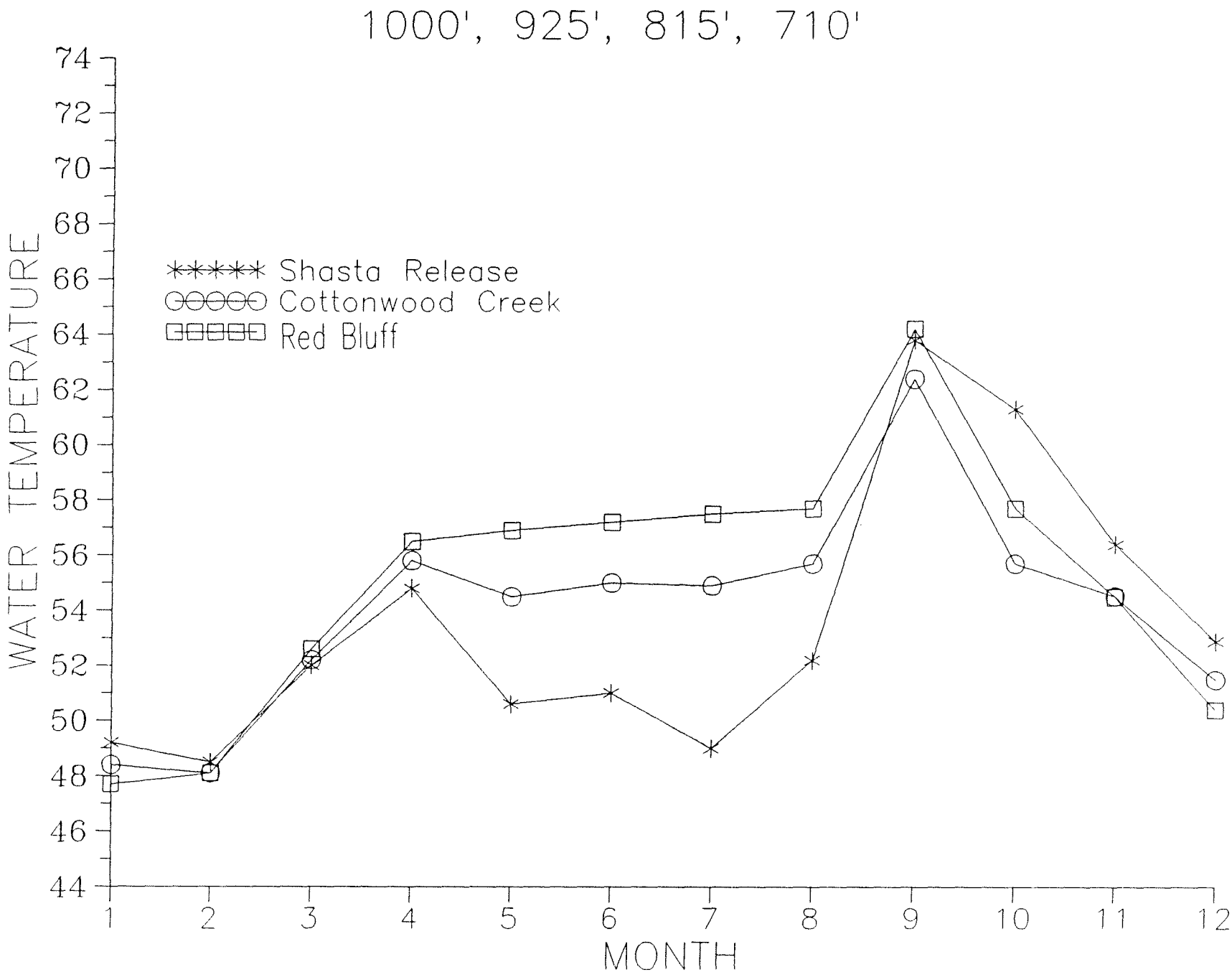
MONTH

1970

1000', 955', 925', 895', 815', 710'




1000', 925', 815', 710'
WATER TEMPERATURE
74
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44
***** Shasta Release
Cottonwood Creek
Red Bluff
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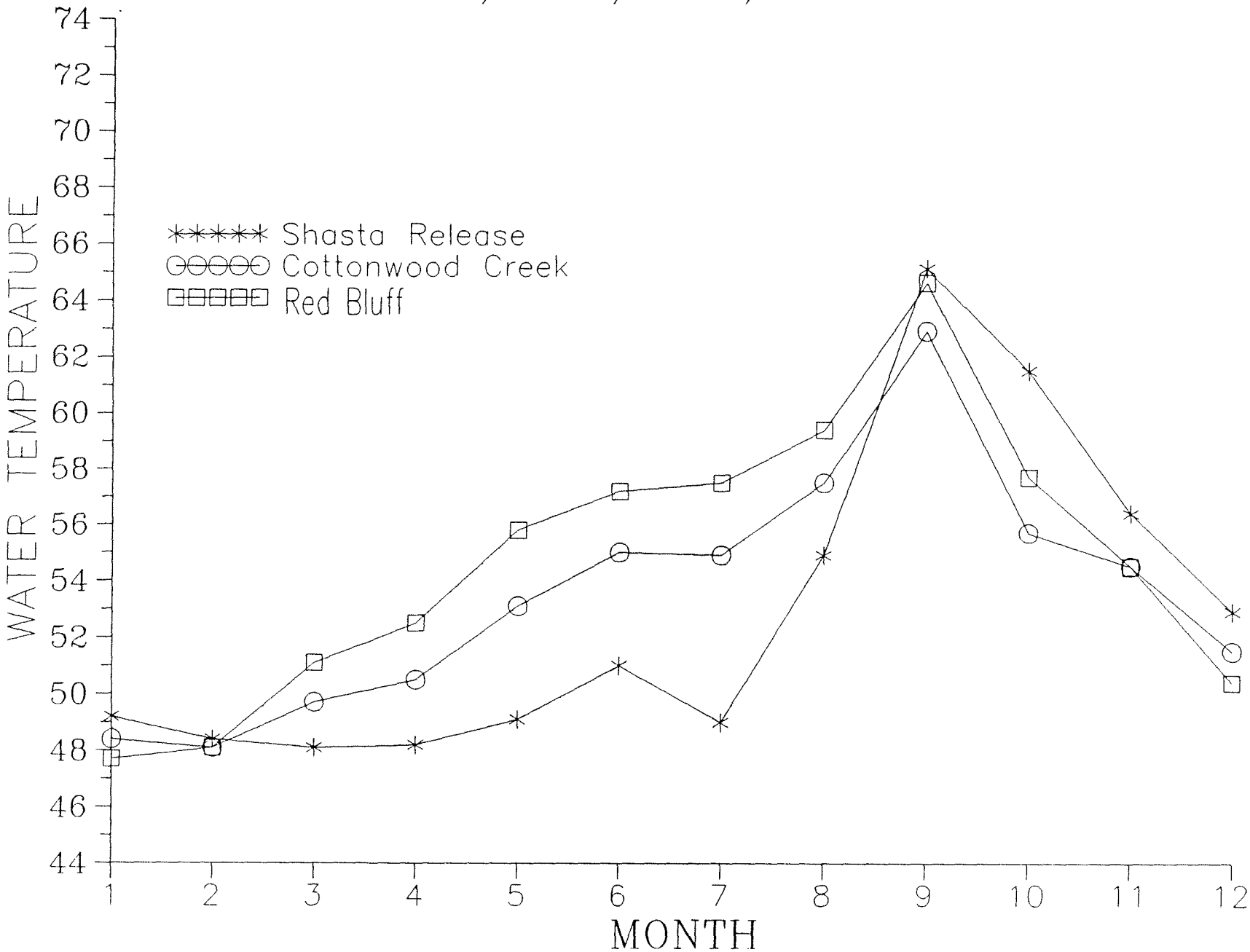
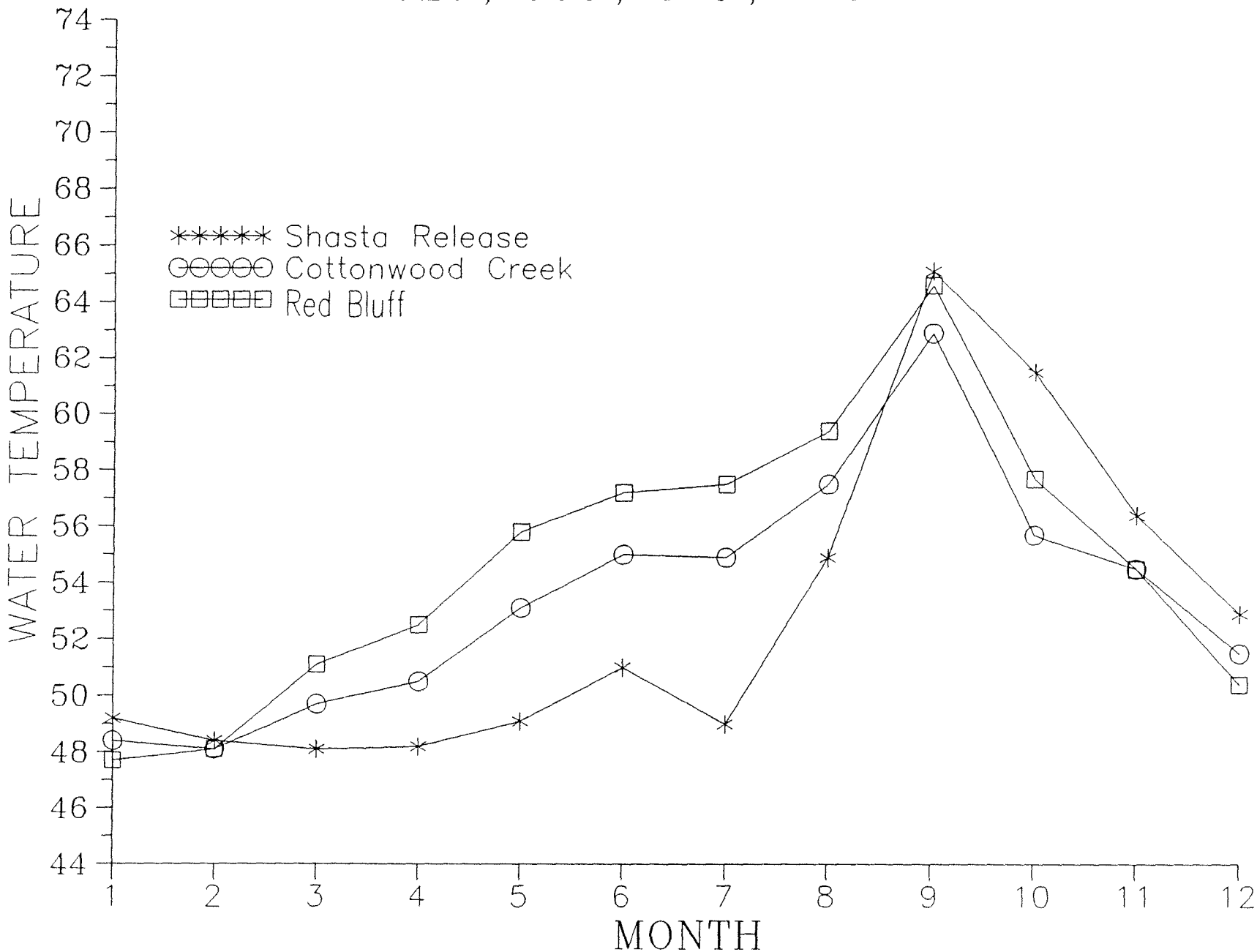
MONTH

1045', 900', 815', 710'

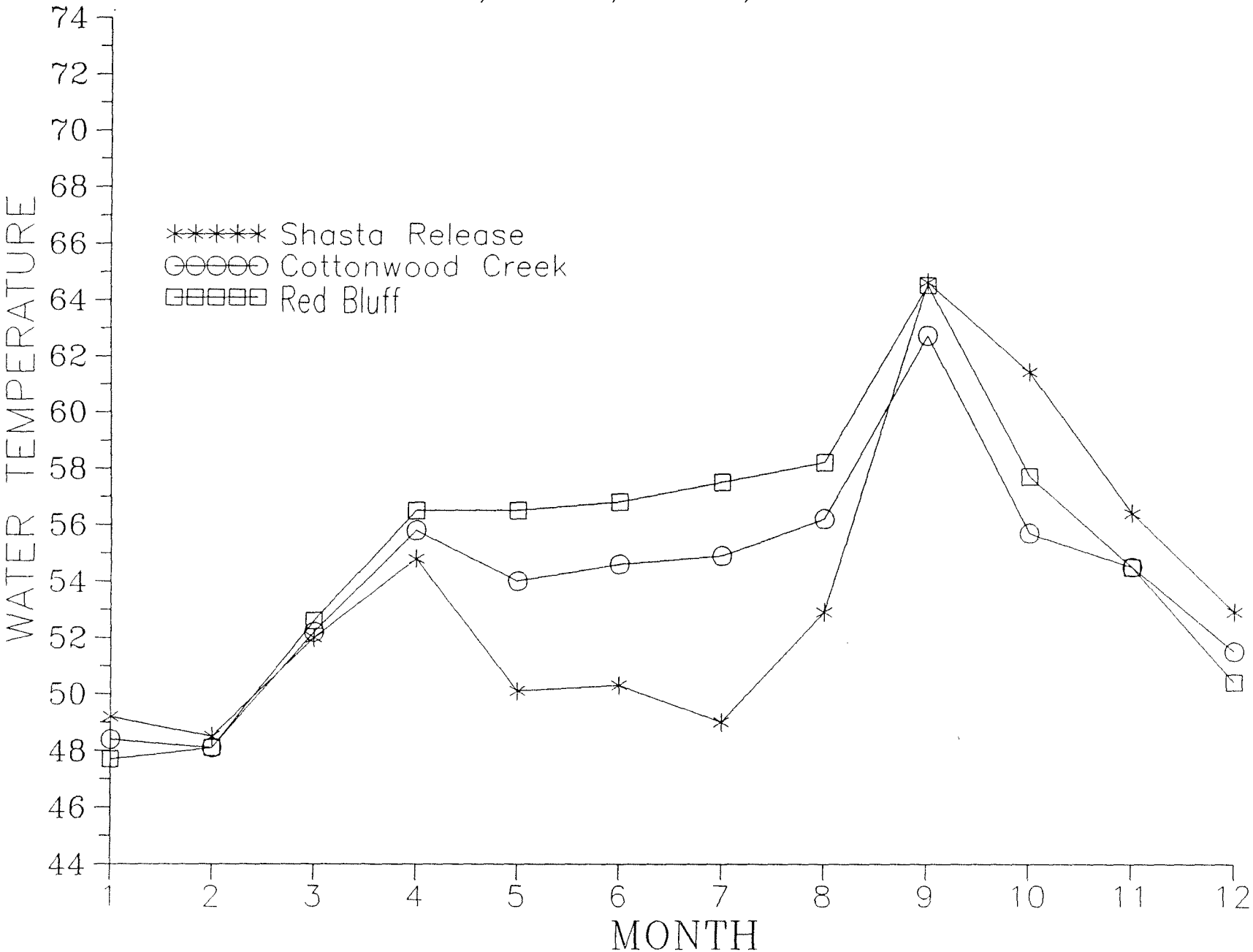


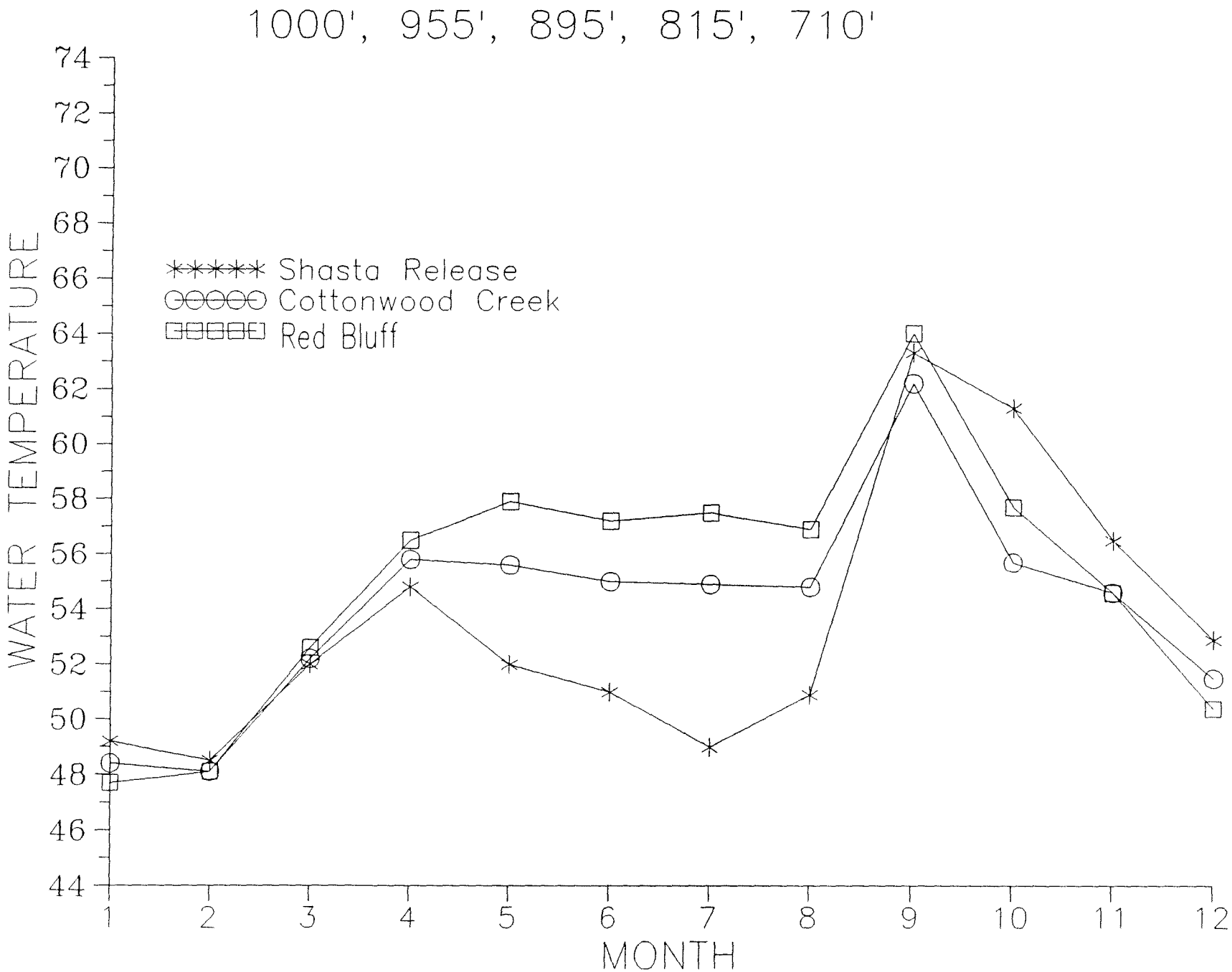
1970

1020', 900', 815', 710'



1000', 900', 815', 710'




1000', 955', 895', 815', 710'
WATER TEMPERATURE
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***** Shasta Release
Cottonwood Creek
Red Bluff
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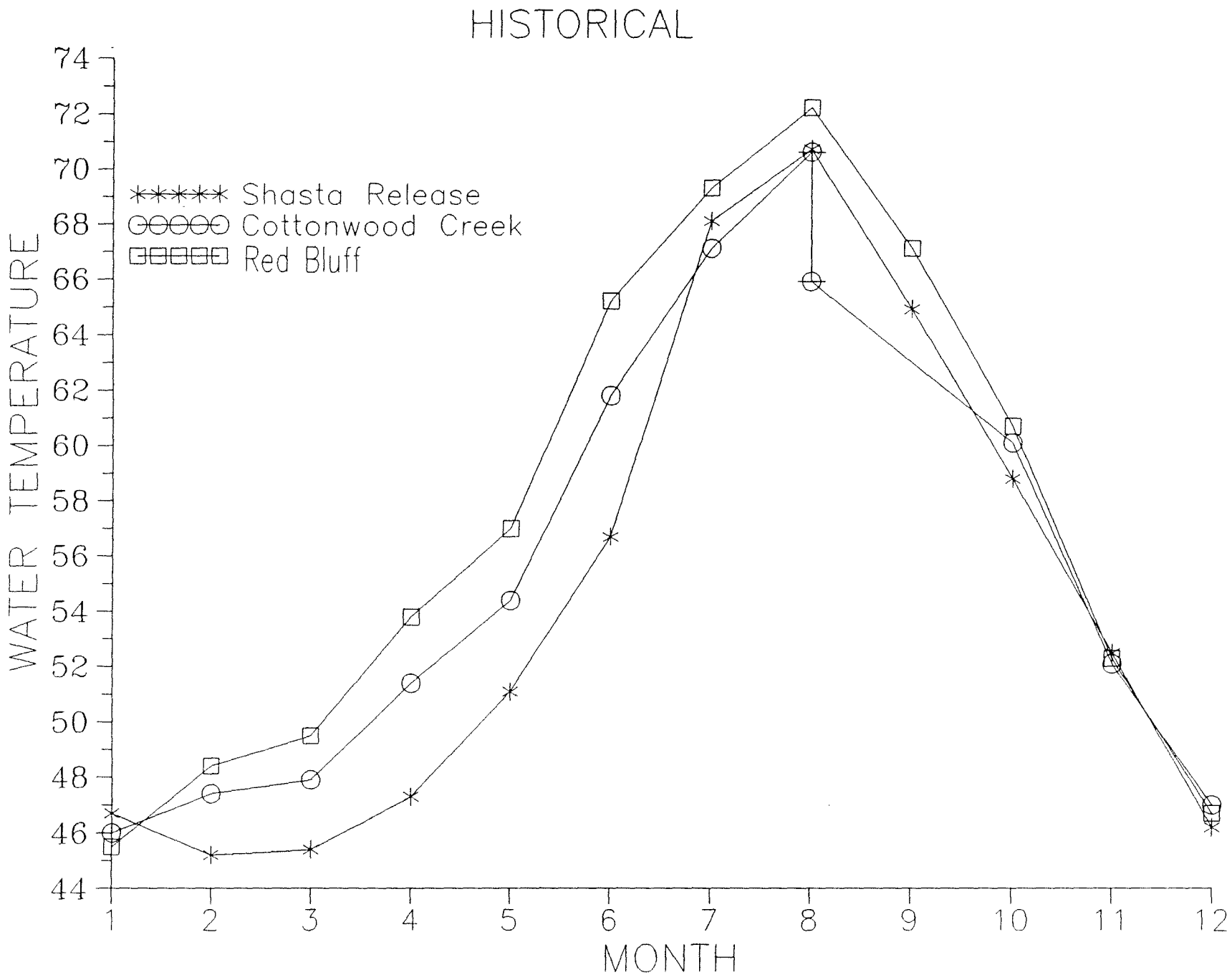
MONTH


HISTORICAL
Shasta Release
Cottonwood Creek
Red Bluff
WATER TEMPERATURE
74
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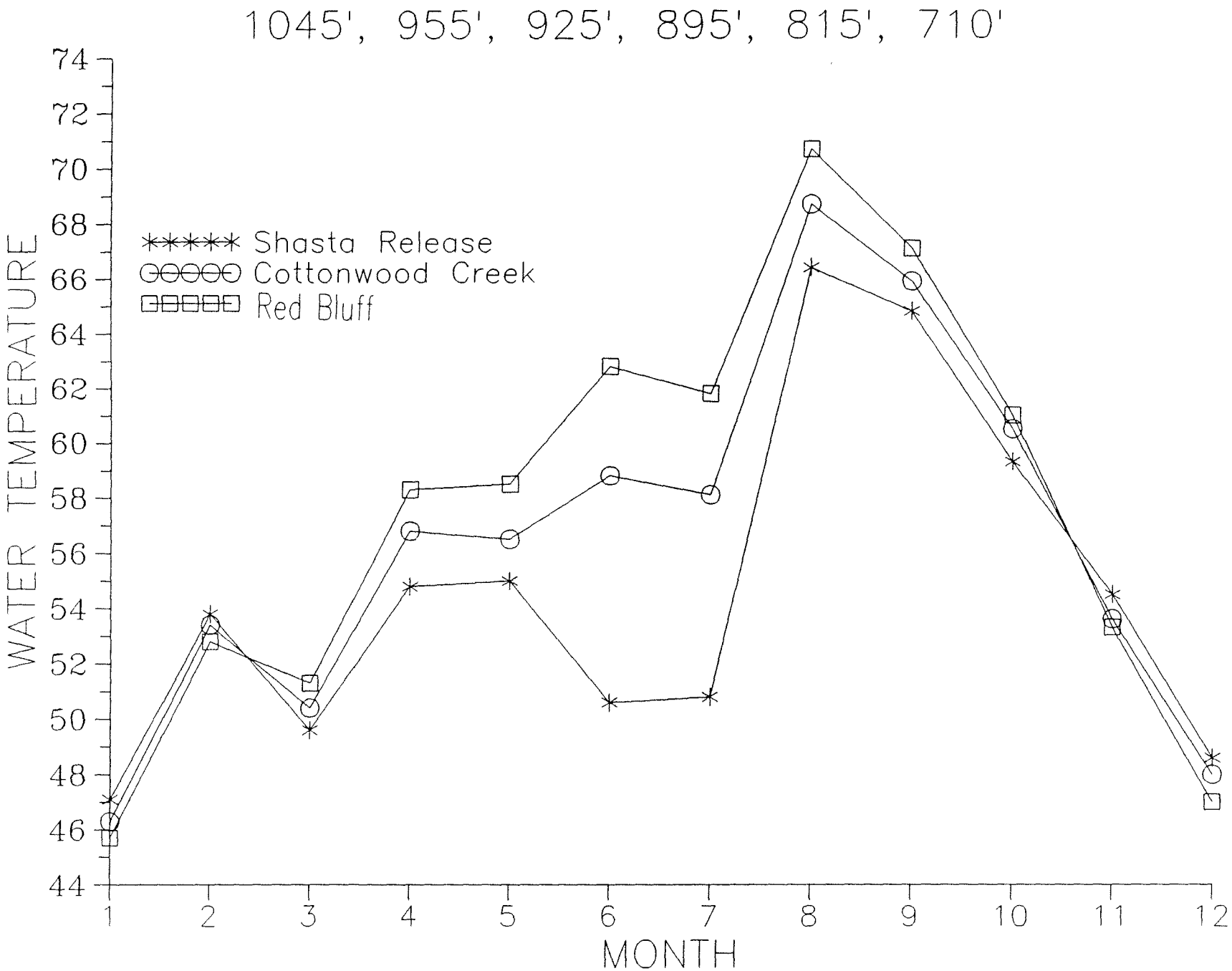
MONTH


1045', 955', 925', 895', 815', 710'
WATER TEMPERATURE
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Shasta Release
Cottonwood Creek
Red Bluff
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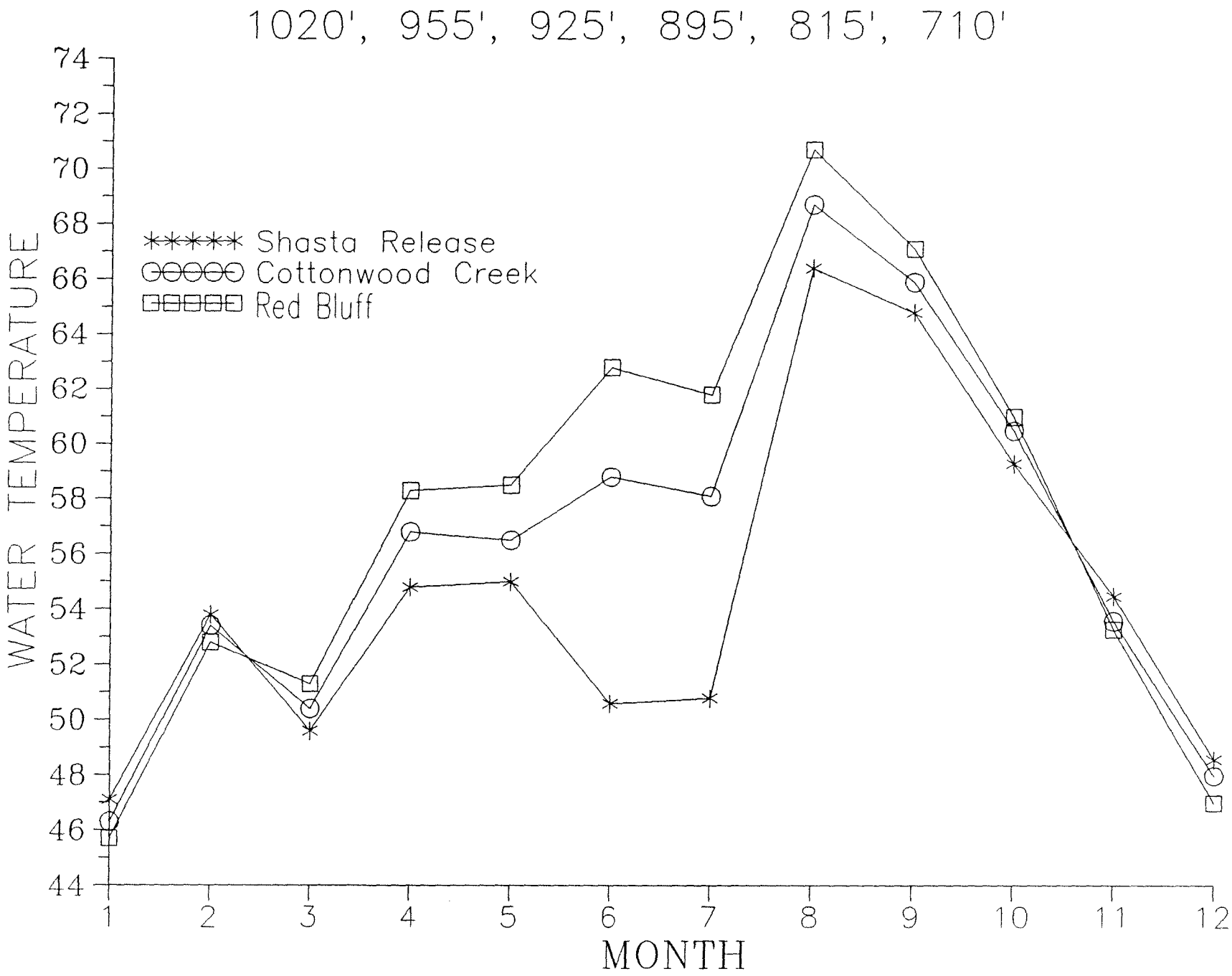
MONTH


1020', 955', 925', 895', 815', 710'
WATER TEMPERATURE
74
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Shasta Release
Cottonwood Creek
Red Bluff
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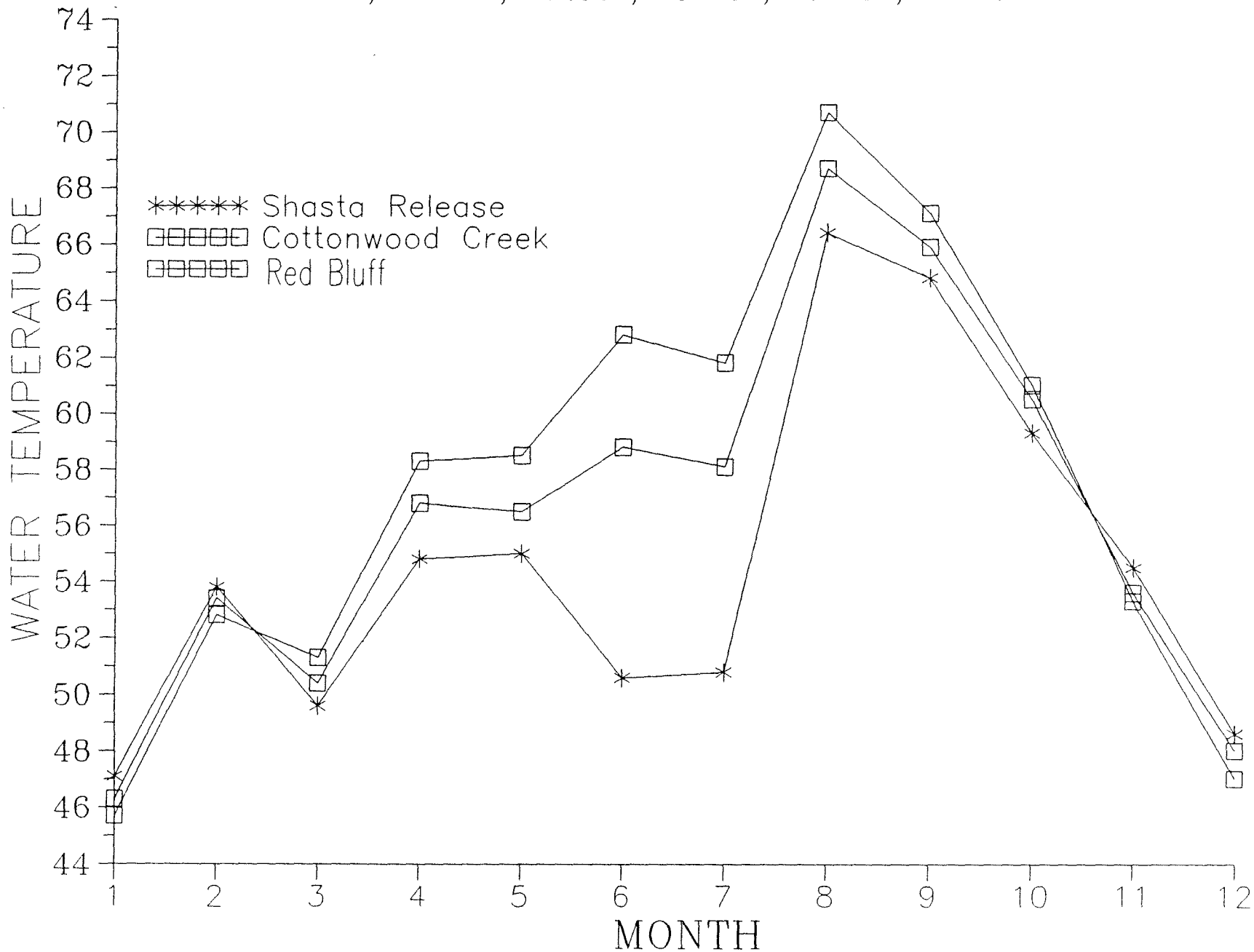
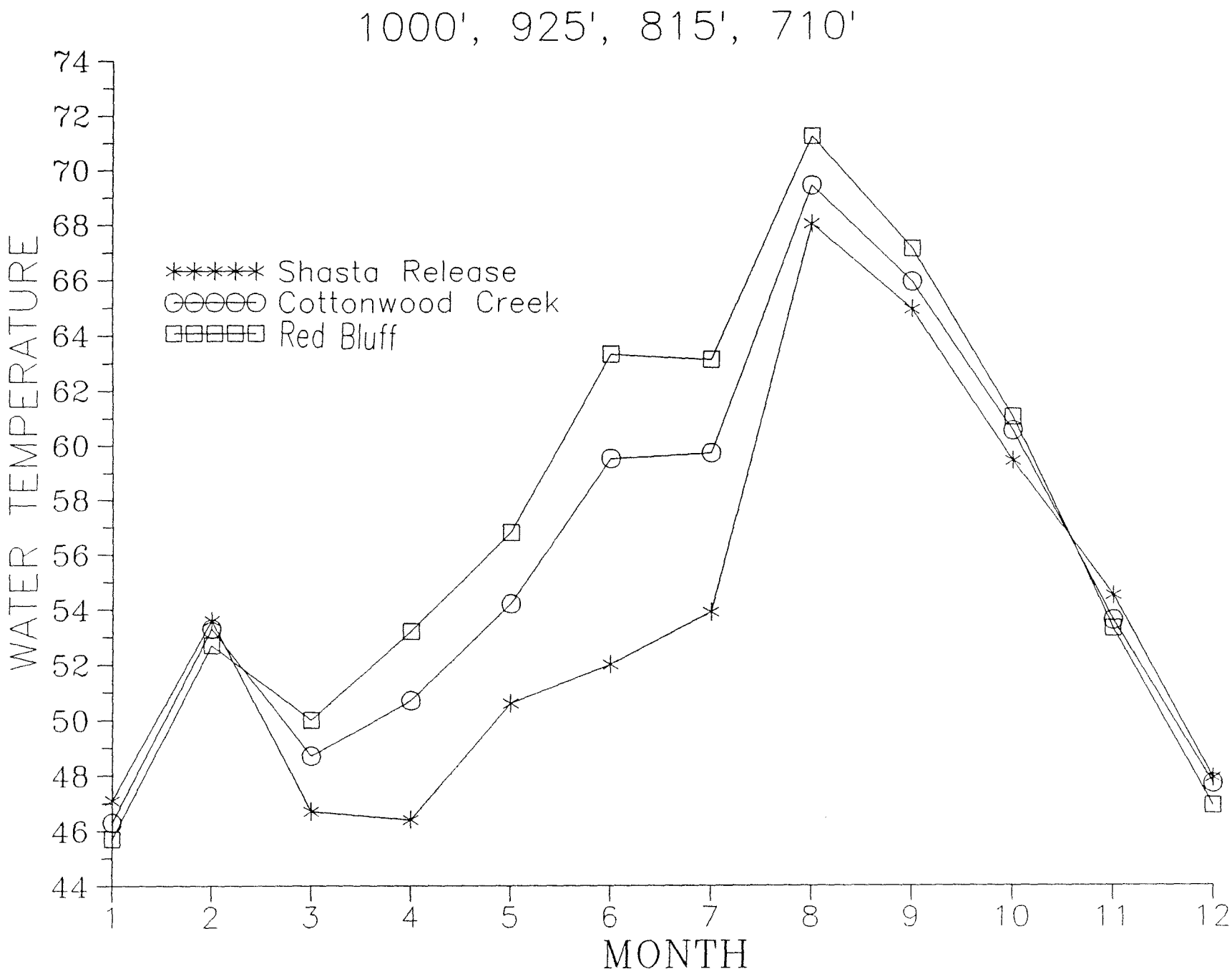
MONTH

1977

1000', 955', 925', 895', 815', 710'

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Shasta Release
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Red Bluff
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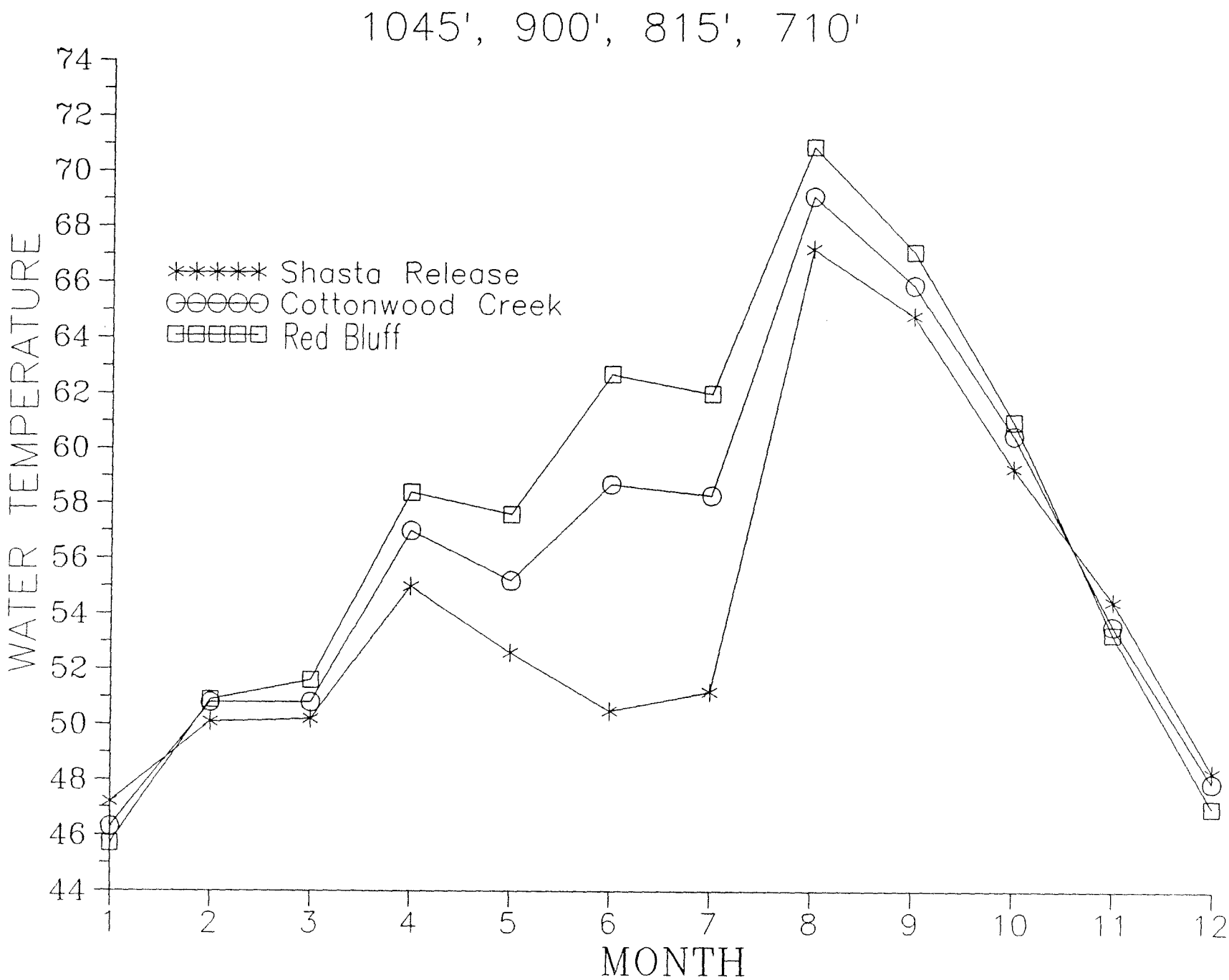
MONTH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Shasta Release
Cottonwood Creek
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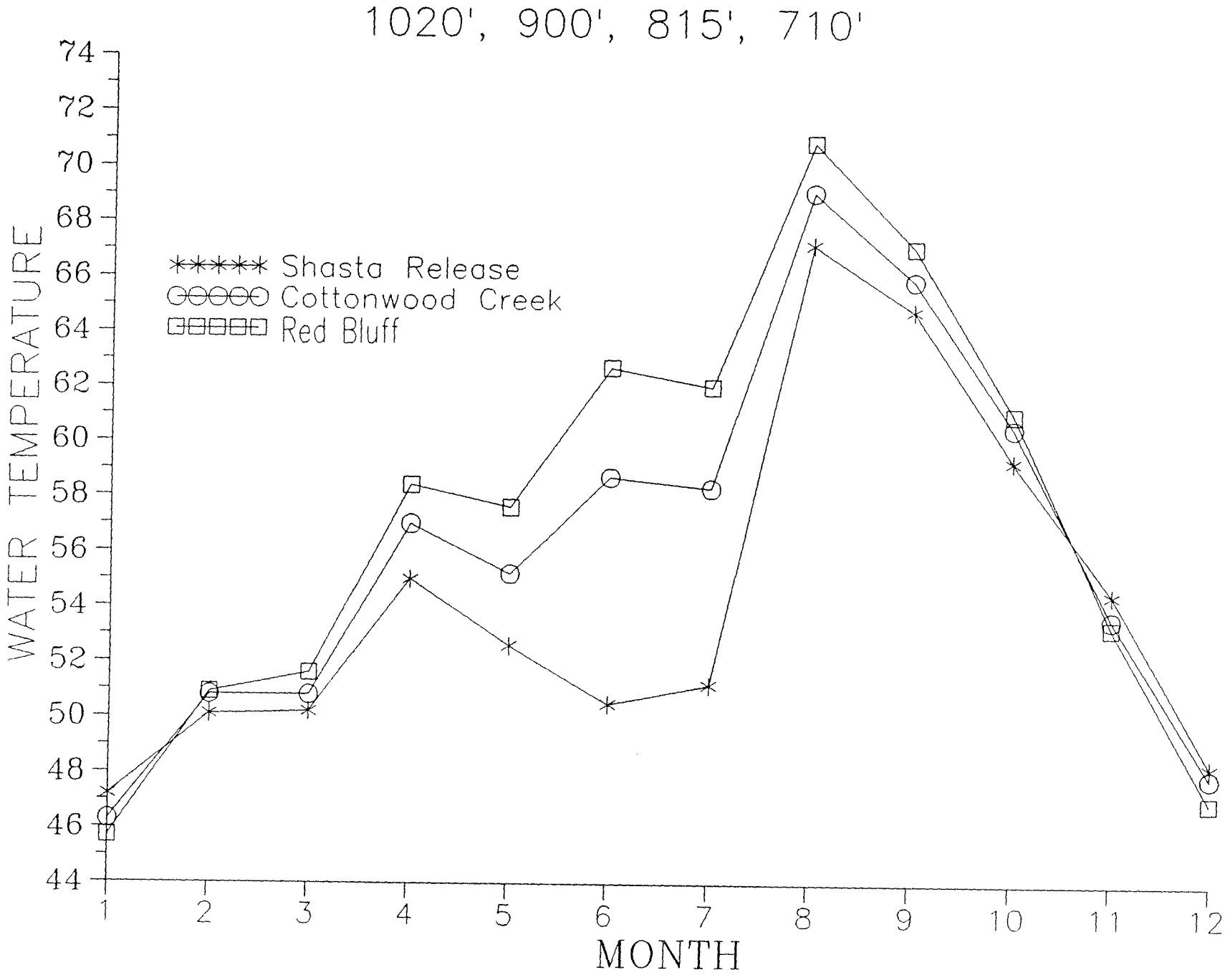
MONTH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Red Bluff
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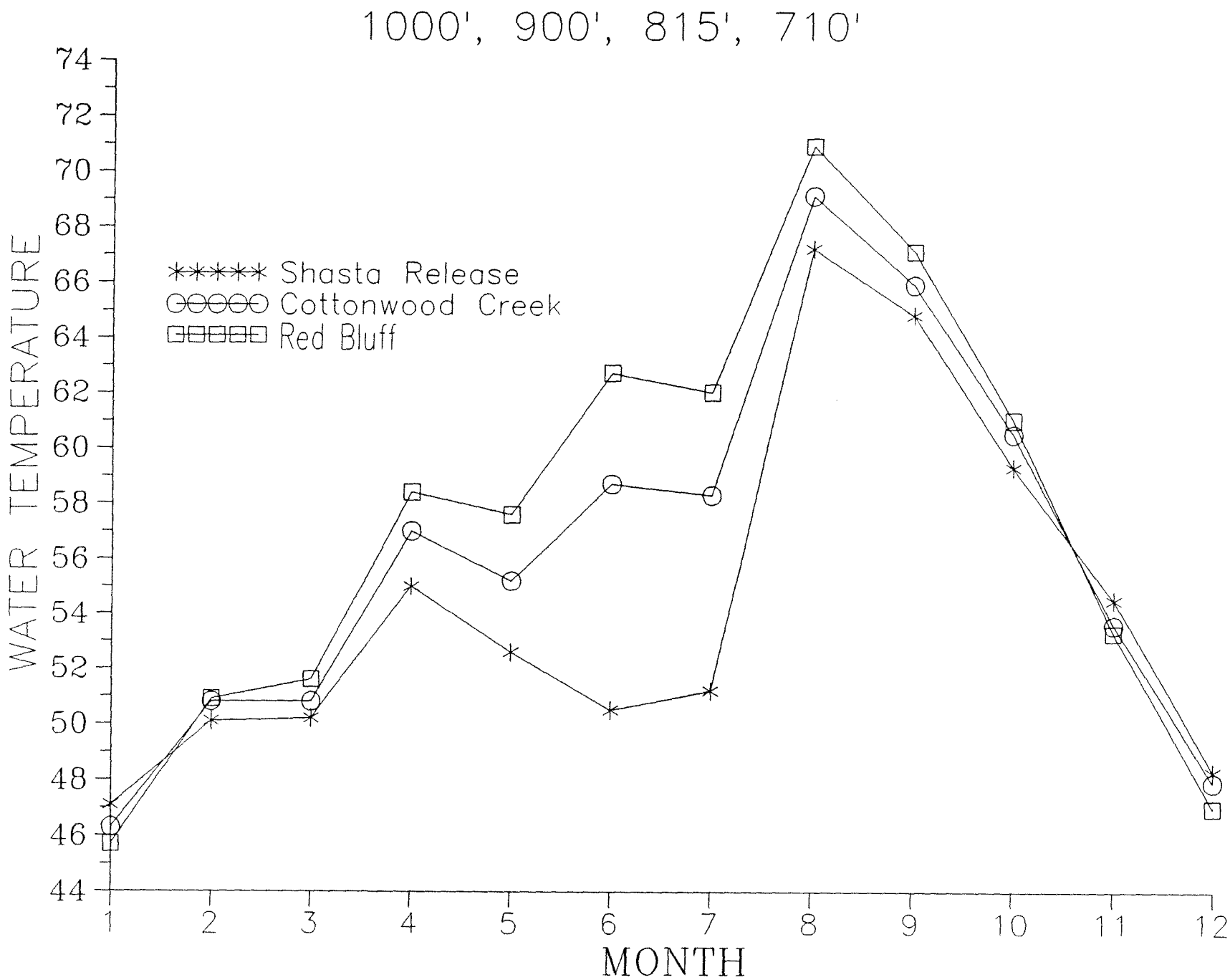
MONTH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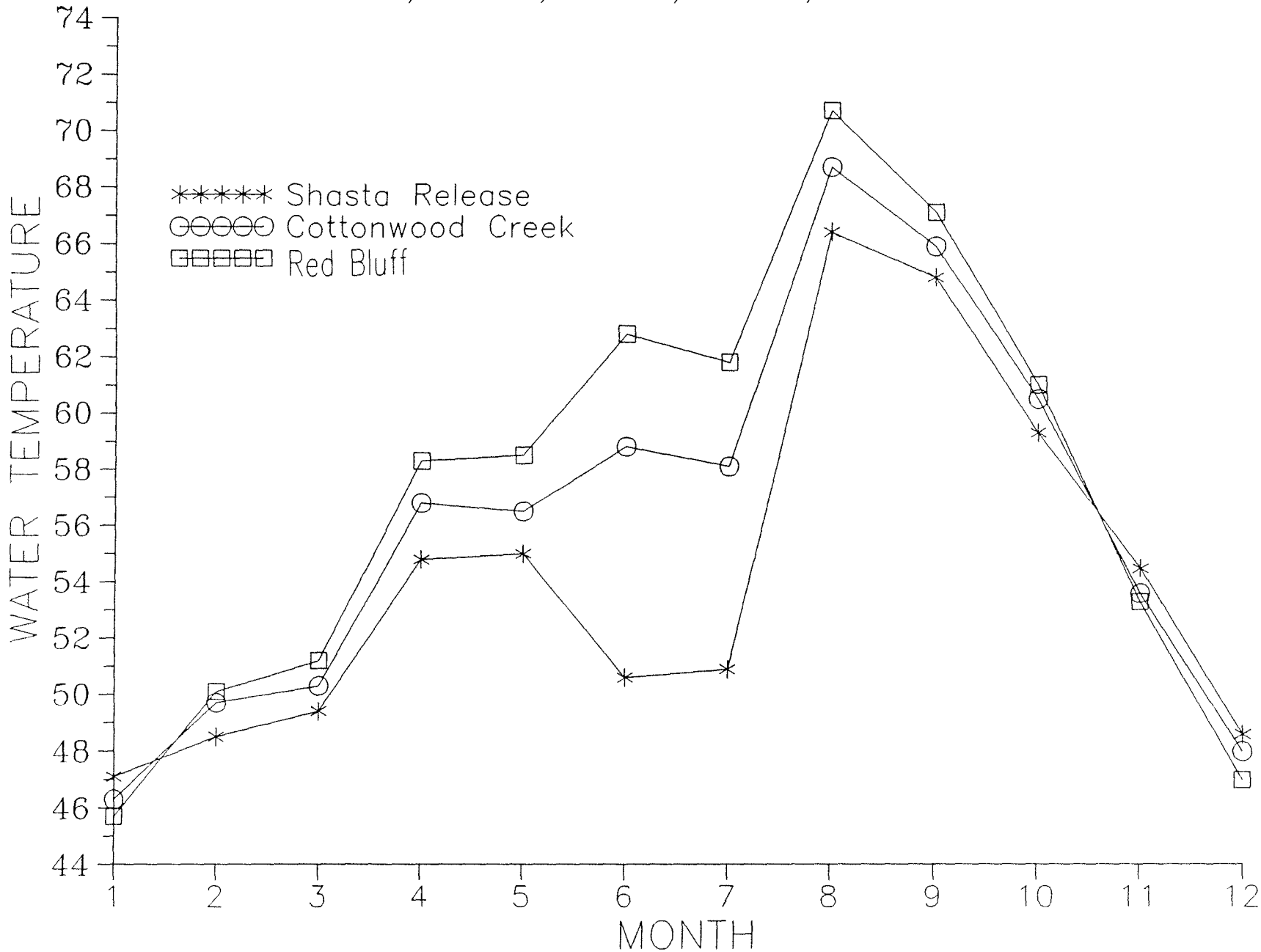

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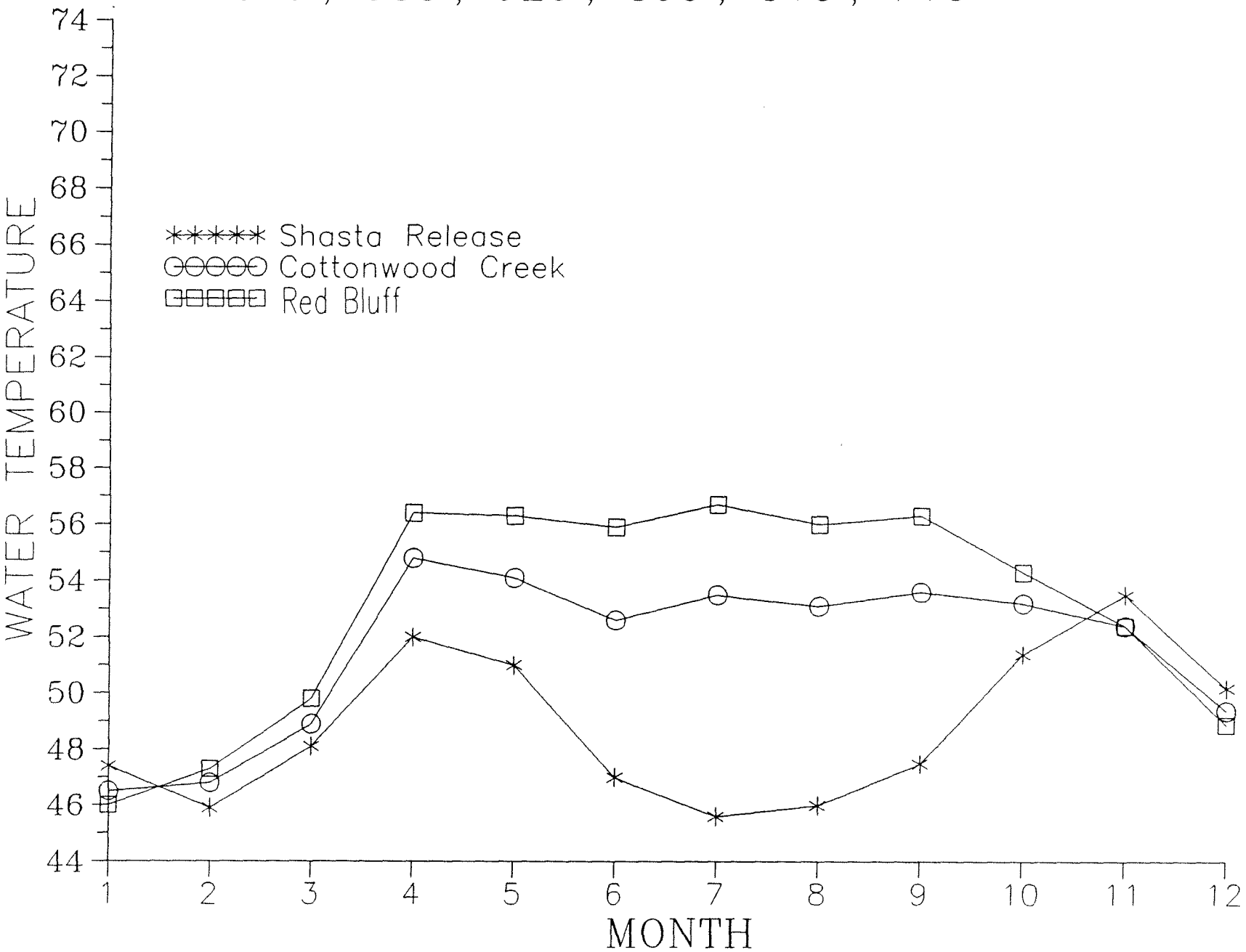

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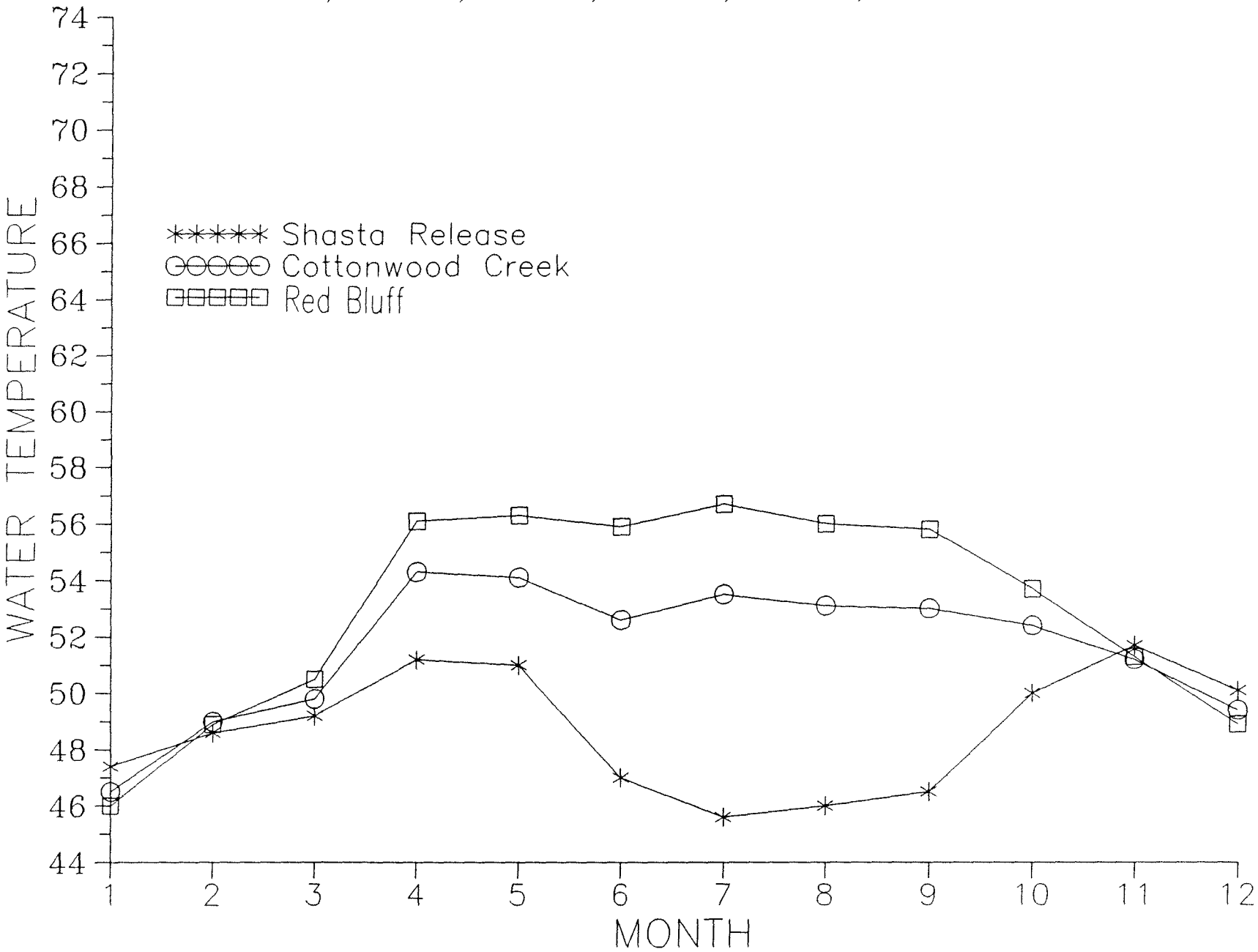

1979

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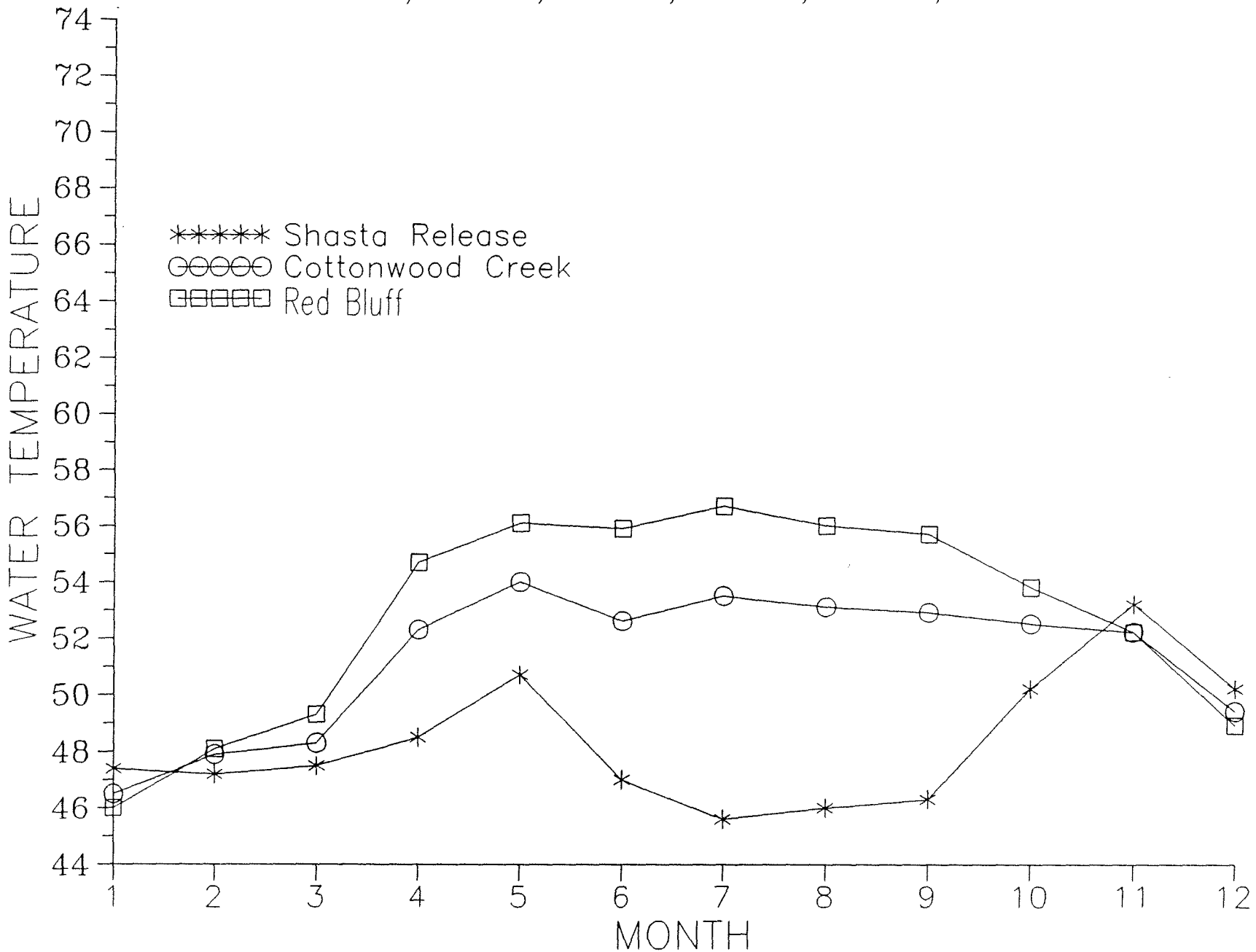

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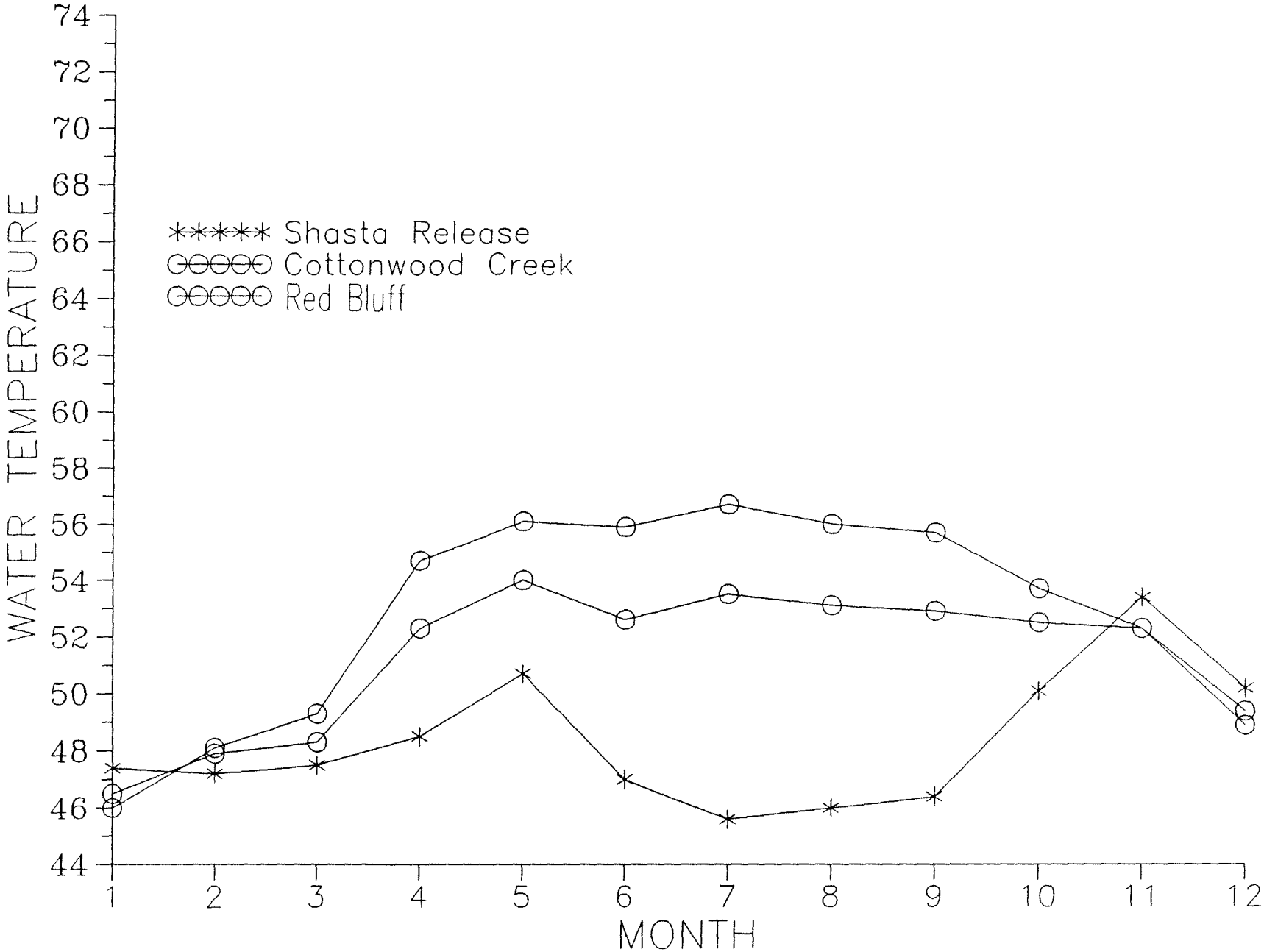

1979

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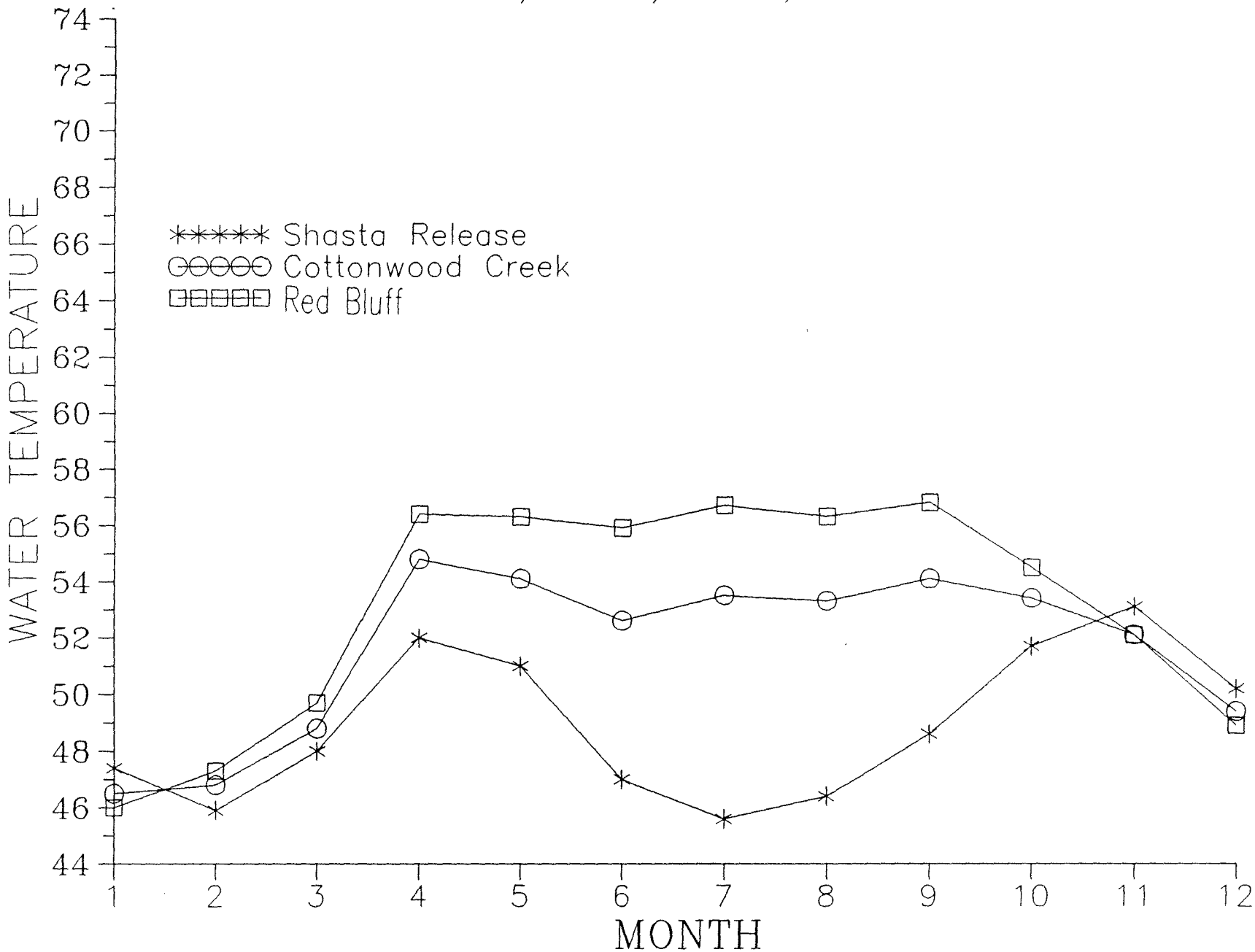

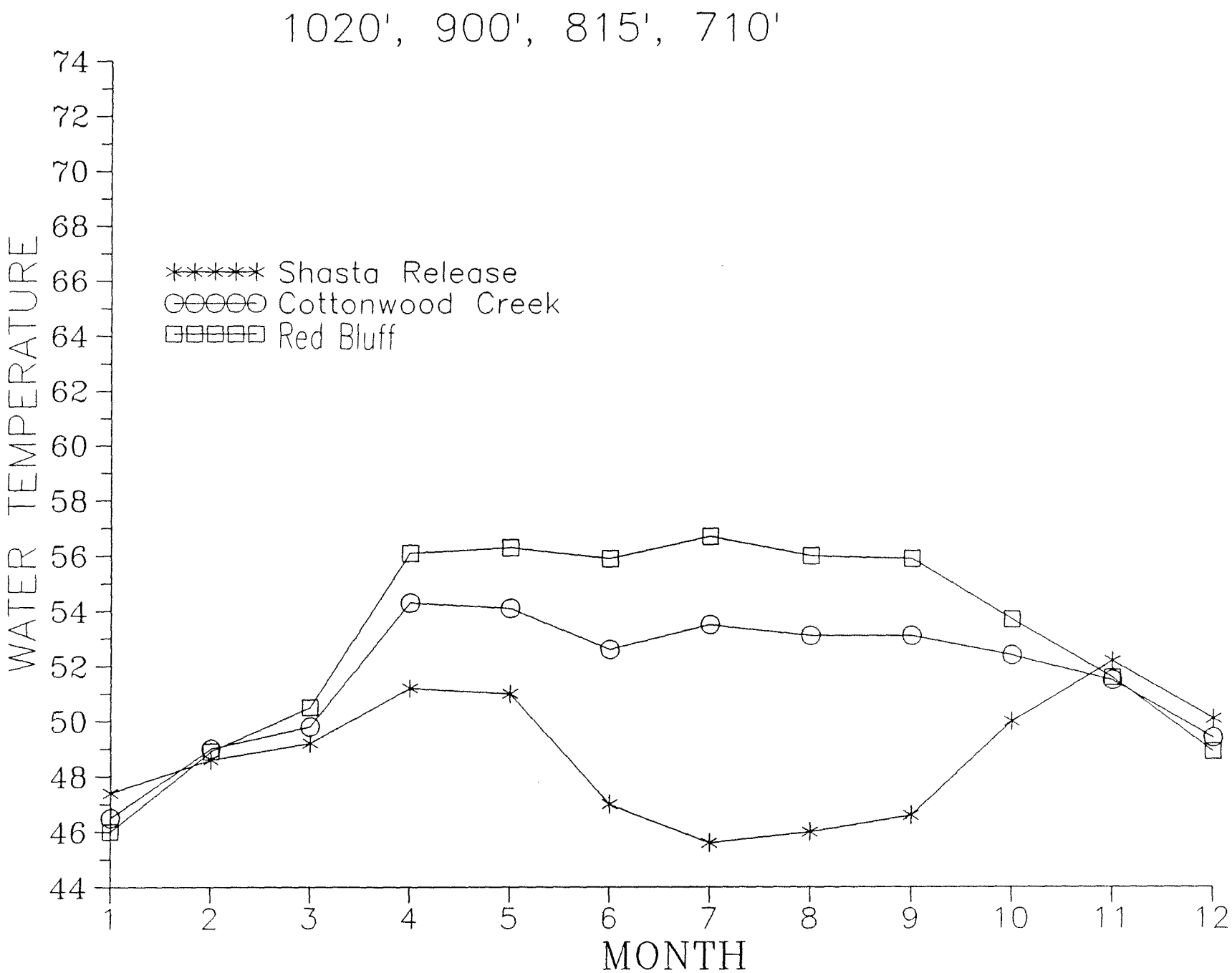
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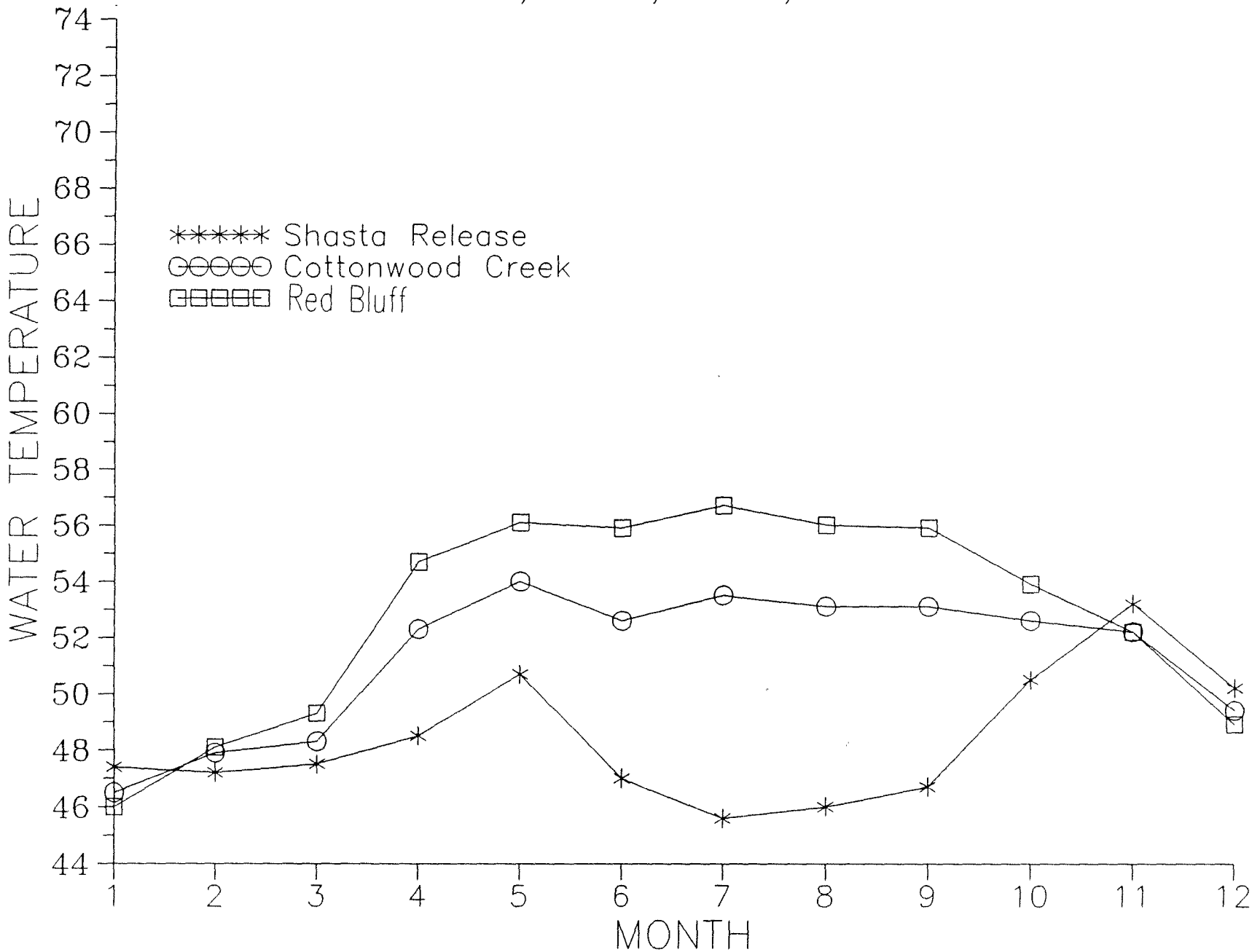
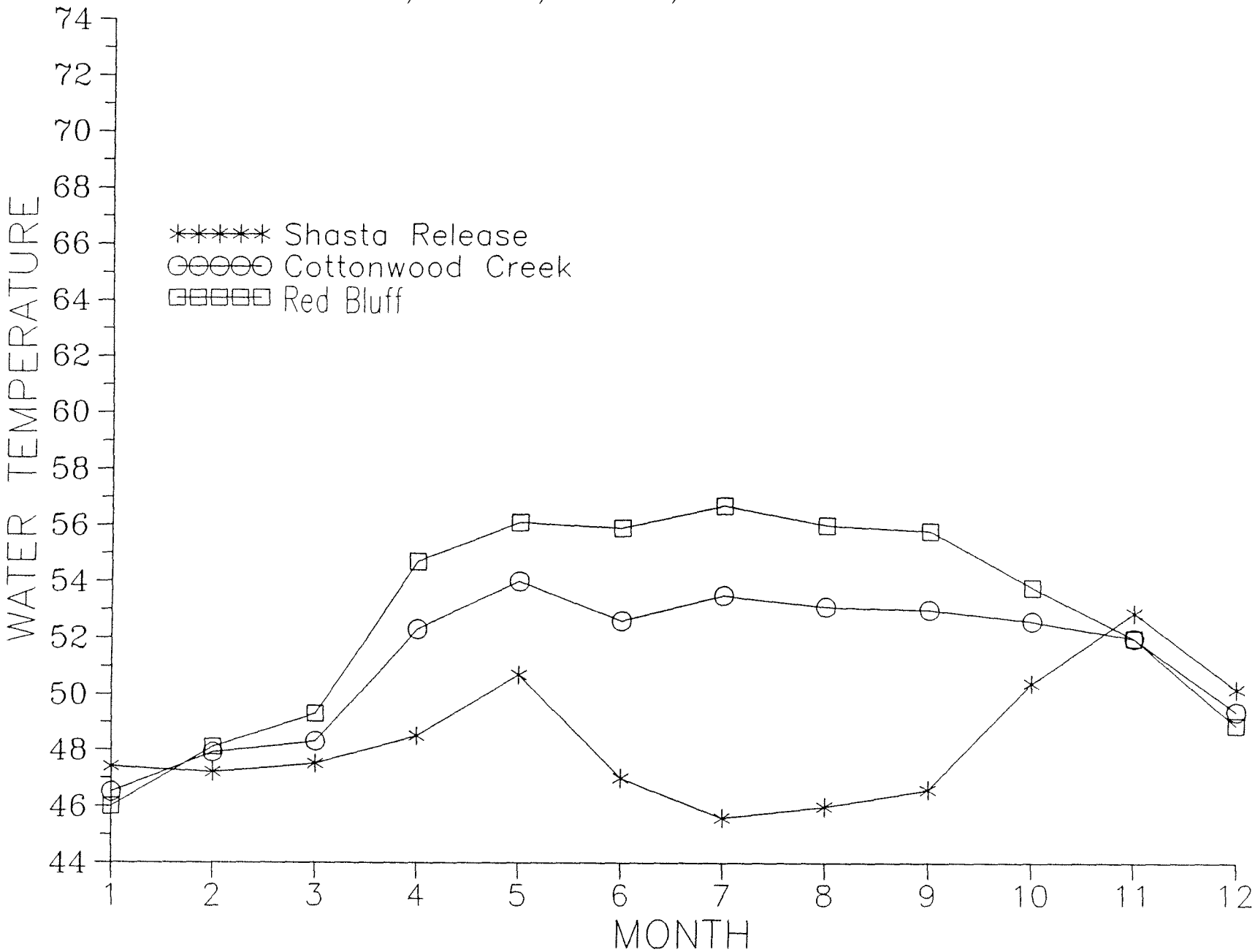
1000', 900', 815', 710'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