REPORT OF

MODIFIED STORM OPERATIONS

BRADBURY DAM, CACHUMA PROJECT

SANTA BARBARA COUNTY, CALIFORNIA

Prepared by
Santa Barbara County
Public Works Department
Water Agency

December 29, 1998

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1.0 INTRODUCTION

During February 1998 the historic operation of Bradbury Dam (Cachuma Reservoir) was changed during two large storm events to reduce downstream flow in the Santa Ynez River. The success of that operation in reducing public risk has prompted the staff of Santa Barbara County Water Agency to summarize the basis for those operations so that such operations may be repeated as conditions warrant. Risk to the yield of the reservoir is also evaluated since the Cachuma Project was authorized for water conservation and was not formally authorized for flood control purposes and thus has no space dedicated to flood control.

Even with modified operations, in the largest storms of record substantial flooding is still possible due to several factors including: 1) limitations in the reduction of releases possible with the existing release works, 2) authorized purposes for the project (and lack of flood pool), and 3) the location of the reservoir in the middle of the watershed (with significant tributaries downstream). Thus, despite the success of the modified operations in reducing significant damage downstream during February 1998, other protective activities, such as channel maintenance, need to be continued since the modified operations have a limited ability to moderate downstream flow.

1.1 Project History

The Cachuma Project was constructed by the United States Bureau of Reclamation (Reclamation) for water conservation purposes in the 1950's. The project was originally proposed to be first in a series of federally built reservoirs on the Santa Ynez River; only one was built (Cachuma). Two smaller reservoirs had been previously built: Gibraltar (by the City of Santa Barbara) and Juncal (by the Montecito Water District). The Cachuma Project has been the principal source of water supply for the south coast part of the county and part of the Santa Ynez Valley since its completion.

During the design of the Cachuma Project, it was recognized that effective flood control in the lower river basin would be best achieved by a dam lower in the watershed. (Cachuma is at the center of the watershed.) A dam proposed for the "Narrows" area would have provided flood protection, but was found to be infeasible in the early 1970's. No other new projects to moderate flows in the main stem of the river have been pursued since the 1970's. Areas in the lower watershed sustained significant damage during the storms of January and February 1969, and to a lesser extent in 1978, 1983, 1993 and 1995 as well. Flows in the Santa Ynez River at Solvang (below Cachuma Reservoir) have exceeded 20,000 cfs seven times, while flows in the river at Los Laureles gage (above the reservoir) have exceeded 20,000 cfs 14 times since the construction of Bradbury Dam, see Table 1. Historical records of operations are available from Reclamation.

Due to predictions of above normal rainfall for water year 1998, County staff evaluated modification of Cachuma Reservoir operations to ascertain whether any reduction in peak releases could be effectuated. Based on these analyses, modifications were suggested to the Flood Control District staff in the fall of 1997. Potential modifications were subsequently discussed with several interested parties including Reclamation (operators of the Dam) and representatives of the Cachuma Member Units (beneficiaries of the project's water supply) as well as downstream interests. During February 1998 elements of the proposed modifications were implemented by Reclamation in consultation with Flood Control staff and others.

1.2 Reason for this Memorandum

After the February, 1998 storms, a number of interested agencies met and requested that Flood Control and Water Agency staff 1) summarize the basis for the modified operations and the effect of modified operations on downstream flow, 2) develop example modeling of historic storms to provide a basis of future operations, and 3) evaluate methods to avoid loss to project yield. This memorandum provides that information. The analyses, including modifications to the FCRIVER model, were performed by Jon Ahlroth, Senior Hydrologist with the Water Agency. The memorandum was written and edited by Robert Almy, Water Agency Manager, (RG. 3804, California), in consultation with the Cachuma Member Unit agencies, the Santa Ynez River Water Conservation District, Reclamation and the Santa Barbara County Flood Control District. Based on their review, Reclamation may request additional analyses; County staff is prepared to respond to such a request.

This memorandum includes a brief discussion of the modeling procedures used to make operational decisions and the changes to the reservoir operations made to date. For a more detailed discussion of the Flood Control runoff routing model (FCRIVER) please refer to the operators manual prepared by Flood Control. For a more detailed discussion of Cachuma operations please refer to the operations manual of the project prepared by Reclamation. (This manual may be reviewed at Reclamation's field office at Bradbury Dam or at the South Central Area Office in Fresno.)

1.3 Summary and Conclusions

After Cachuma has spilled, modification of operations during significant storms may provide health and safety benefits under wet watershed conditions. Reduction of downstream releases during storm events may be achieved through a combination of three changes to the "normal operations":

1 creation of reservoir capacity to accommodate part of storm runoff,
2 release of initial storm runoff up to a rate based on storm magnitude, and
3 surcharge during peak reservoir inflow.

Public safety and project yield are of paramount importance. To protect water supply and to be certain that modified operations do not add to peak downstream flows, several important factors are evaluated as part of the modified operations. These factors are:

1 quantitative precipitation forecasts (QPF) for each storm,
2 watershed conditions, particularly remaining watershed runoff, and
3 response of downstream tributaries to precipitation.

These factors are essential to any operational decisions intended to reduce down stream flow during reservoir releases.

2.0 HISTORIC OPERATIONS OF BRADBURY DAM

Bradbury Dam was completed in 1956 and forms the largest reservoir on the Santa Ynez River. It is located near the center of the watershed; the lake has a drainage of 417 square miles and 480 square miles are drained below the dam. Since the Cachuma Project was constructed for conservation purposes, no space in the reservoir is made available for flood control purposes. However the reservoir has affected downstream flows during storm events, particularly when significant storage existed at the beginning of a significant storm event.

2.1 Reservoir and Spillway Characteristics

Cachuma Reservoir is the largest of the three reservoirs on the Santa Ynez River; it is also the furthest down the river, 48.7 river miles from the Pacific Ocean. The reservoir is formed by Bradbury Dam, a 205 foot high earth-filled structure with a 2,975 foot crest length. The crest of the dam is at elevation 766 feet MSL. The spillway is a broad crested weir in the south abutment of the dam. The spillway invert is at elevation 720 feet. The top of the spillway comprises four bays, each equipped with a 50 ft. wide by 31 ft. high radial gate which opens from the bottom. (The top 1.0 foot of each gate is called the "splashboard" and effectively increases the height, thus freeboard, to prevent wind waves and small water level changes from spilling over the gates.) The rated capacity of the spillway is approximately 160,000 cubic feet per second (cfs).

The normal full operating level of the reservoir is elevation 750 MSL with the gates closed. When constructed, the reservoir had a capacity of 204,874 acre feet, with a surface area of 3,090 acres at elevation 750. Based on a silt survey performed in 1990, the capacity of the reservoir had been reduced to 190,409 with a corresponding surface area of 3,043 acres. Recent modifications to address Safety of Dams program concerns have not changed the volume or operational characteristics of the reservoir.

The normal gate operation rules are summarized graphically in Figure 1. This figure shows prescribed gate opening as a function of lake elevation and is sometimes referred to as the "rule curve". The gate settings prescribed in this figure allow the operation of the reservoir based on no other information than lake elevation. Some flexibility in operations is due to the "envelope" between the upper and lower limits of the gate settings shown for each lake level above elevation 750.0 ft.

Due to the size of the reservoir, some attenuation of peak stream flow occurs as runoff passes through the reservoir, even when full, due to the delay between peak inflow and release under the existing operational rule curve. Previous evaluation by the County Flood Control District suggests that the attenuation results in a few percent reduction in downstream releases (compared to peak inflow). Since the "rule curve" is actually an operational envelope, past operations have recognized that some additional reduction of peak flow occurs if the reservoir is allowed to rise to the maximum level allowed (within the envelope) during peak inflow while holding the gate opening to the minimum.

2.2 Normal Flood Routing

The watershed area above Bradbury Dam is 417 square miles, 216 sq. mi. of which are above Gibraltar reservoir. Because Gibraltar reservoir capacity is relatively small as a function of watershed runoff (thus it generally fills early in the rainy season), and because the reservoir has no flood control pool, its operation has little effect on the operation of Cachuma Reservoir during large runoff events.

Historically, operations of Cachuma Reservoir have followed the operating "rule" curve (Figure 1). Until the reservoir level is above elevation 750, no releases are made. As the lake elevation rises above elevation 750, the gates are opened, depending on the lake elevation. (Since the gates were viewed as "automatic", the gates often did not begin opening until the lake level rose to elevation 750.5, the "top" of the operating envelope. The gates are now operated on a "manual" basis, thus they may be opened at or before the lake reaches elevation 750.0). Gate setting (opening) was based on lake elevation, meaning that the response of the gates followed increased inflow. This operation does not rely on rainfall or runoff prediction and thus is not sensitive to data availability or error in prediction of parameters such as inflow. Under this operation certain key design features of the dam, reservoir, and spillway have excess capability. For example gate freeboard (the distance the top of the gate extends above water surface) increases as the gates are opened, see Figure 2.

Under normal operations at Bradbury Dam, storm runoff into Lake Cachuma is stored until the reservoir elevation exceeds 750 feet, MSL. Above that elevation the reservoir spillway gates are opened to release the storm inflow. The spillway gates are opened as a direct function of the lake elevation above the 750 foot full level. The effect of this type of operation on routing a storm through a full reservoir is to produce an outflow hydrograph with a peak flow a few percent lower in magnitude than the inflow peak, and delayed in time (compared to the inflow peak) by 2 to 3 hours. Therefore, flows in the Santa Ynez River below Bradbury Dam are generally reduced somewhat (as to peak flow magnitudes) as a result of the normal operations at the dam when the lake is spilling. When lake level is below elevation 750, no releases are normally made during storm events, and thus peak downstream flow may be entirely due to tributaries below the dam if sufficient storage exists at the beginning of a storm event.

2.3 Summary of Selected Storm Events

A summary of historic operation of selected storms is shown in Figures 3 through 6. These four storms are illustrative of varied watershed conditions and storm magnitudes and intensities. The figures are actually printouts of Flood Control's FCRIVER model for each storm, rather than plots of the recorded flow and reservoir operations. Based on staff evaluations (Appendix A), the model representations closely match the actual measurements made during each storm. As discussed in a subsequent section, the FCRIVER model was in fact developed and calibrated against historic storms such as January 1969.

Historic operations are shown for the following storm:

1 January 23-26, 1969 (largest storm of record, wet watershed), Figure 3.

Operations based on the historic rule curve are shown for the following storms:

2 February 1-3, 1998 (large storm with the lake level below 750), Figures 4a and 4b,
3 February 6-8, 1998 (moderate storm with a wet watershed), Figure 5b, and
4 February 23-24, 1998 (large storm a wet watershed), Figure 6.

A summary of operations and downstream flows is provided below for each storm as well.

- January 23-26, 1969

The January 1969 storm is the largest on record. (Reclamation has determined the storm runoff has a return interval of 1400 years based on paleoflood records.) Watershed conditions were extremely wet; in fact light rain occurred for twenty hours before the most intense part of the storm. The "antecedent index", a measure of watershed runoff potential was 3.0 at the beginning of the storm (very wet). The upper watershed had received over 15 inches of rain in the five days prior to the storm. Cachuma reservoir was spilling approximately 2,000 cfs and was full when the peak runoff event began. The peak runoff was caused by nearly 8 inches of rain in 8 hours. Peak inflow was 89,000 cfs, peak releases were 80,000 cfs. Review of Figure 3 shows the delay effect of the reservoir operated pursuant to Figure 1 (the "rule curve"); the peak inflow occurred approximately two hours before peak releases. Peak inflow caused the lake to rise to elevation 755 with a gate opening of approximately 16 feet. The reduction in the peak release was approximately 9,000 cfs (10% of peak flow). Maximum flow in the Lompoc area was 80,000 cfs which resulted in widespread damage. Potential reduction to the peak releases for this storm is discussed in Section 4.4

- February 1-3, 1998

The February 1-3, 1998 storm was of long duration and of moderate size. Initial watershed conditions were only moderately wet; but since the most intense part occurred late in the storm, the main part of the storm runoff resulted from very wet watershed conditions. The initial antecedent index was 5.6 at the beginning of the storm. The upper watershed had received nearly 12 inches of rain in the 47 hours of the storm. Cachuma reservoir was at elevation 732.4 (with 48,300 AF of available storage) when the storm event began. The peak runoff was caused by 4.5 inches of rainfall over the last 16 hours of the storm. Peak inflow was 40,000 cfs, peak releases were 22,400 cfs (Reclamation operations records). Review of Figure 4a shows the effect of available storage in the reservoir prior to the storm; no outflow (releases) occurred until the final rainfall peak, (and well after the peak contribution of downstream tributaries). The peak inflow occurred approximately four to five hours before peak releases. Peak inflow caused the lake to rise to elevation 751.58 with a gate opening of approximately 4.2 feet. The reduction in the peak release was approximately 17,600 cfs (44% of peak inflow) and was primarily due to the available storage at the beginning of the storm. Maximum flow in the Lompoc area was 27,000 cfs which resulted in some inundation of low-lying areas. Potential further reduction to the peak releases for this storm is discussed in Section 4.4.

Figure 4b shows modeling of the storm assuming a reservoir in a spill condition at the beginning of the storm. If the reservoir storage had not been available before the storm (i.e. if the reservoir had been at or near a spill condition), and if the rule curve had been followed throughout the storm, significant reservoir releases during the second element of the storm would have contributed to peak tributary runoff. The resulting flows in the Lompoc area are estimated to have been 43,000 cfs. Combined flow in the Lompoc area from the last element of the storm would have resulted in flow above 40,000 cfs for approximately 8 hours.

- February 6-8, 1998

The February 6-8, 1998 storm was of moderate size and consisted of two rainfall events separated by roughly thirty hours. Initial watershed conditions were wet, and about 2.7 inches of rainfall fell over the thirty hour period leading up to the main part of the storm. The antecedent index was 3.1 at the beginning of the storm. The upper watershed received a total of 6.8 inches of rain in the 43 hours of the storm. Reclamation was maintaining the reservoir below "full" to provide operational flexibility, thus the reservoir was at elevation 745.7 ft. (with 12,800 AF of available storage) when the storm event began. The peak runoff was caused by the later element of the storm comprising 3.7 inches of rainfall in 5 hours. Peak inflow was 27,300 cfs, peak releases were held to 16,100 cfs (Reclamation operations records) and occurred five hours after peak inflow. Review of Figure 5a shows the effect of available storage in the reservoir prior to the storm and gateholding during the storm; no significant outflow occurred until the final rainfall peak, (and well after the peak contribution of downstream tributaries). Peak inflow caused the lake to rise to elevation 752.8 ft. with a gate opening of approximately 2.9 feet. The attenuation (reduction) in the peak release was due to the available storage at the beginning of the storm and holding the maximum gate opening to approximately 2.9 feet. Maximum flow in the Lompoc area was 19,600 cfs which resulted in some inundation of low-lying areas.

For comparison, Figure 5b shows the effects of standard operations on runoff from this storm, (initial reservoir at elevation 750 ft. and no gateholding). Under standard operations the flows in the Lompoc area are estimated to have been 20% higher. Potential further reduction to the peak releases for this storm is discussed in Section 4.4.

- February 23-24, 1998

The storm of February 23-24, 1998 was of moderate size but consisted of a single rainfall event which generated 7.9 inches at Gibraltar Dam in 16 hours. Initial watershed conditions were wet; the antecedent index was 3.6 at the beginning of the storm. Reclamation was maintaining the reservoir below "full" to provide operational flexibility, thus the reservoir was at elevation 746 ft. (with 11,900 AF of available storage) when the storm event began, (Figure 12). The peak runoff was caused by over four inches of rainfall in four hours. Peak inflow was 50,000 cfs. If no modified operations had been implemented, the FCRIVER model predicts peak inflow would have been 46,400 cfs with peak releases of 40,800 cfs occurring three hours after peak inflow, (Figure 6). (As discussed in section 3.5.3, in this case the model under-predicted peak flow as compared to measured peak flow.)

The model predicts peak inflow would have caused the lake to rise to elevation 752.87 ft. with a gate opening of 7.93 feet if no modification of operations had occurred. The reduction in the peak release would have been 5,500 cfs (12 % of peak flow). Maximum estimated flow in the Lompoc area would have been 42,600 cfs and would have resulted in significant inundation of low-lying areas, and potential damage. Actual operational modifications undertaken to reduce peak releases from this storm are discussed in Section 4.4.

2.4 Incidental Flood Control

Depending on conditions, flow in the Santa Ynez River below Bradbury Dam may be reduced by one or more factors including: 1) capture of inflow prior to the reservoir reaching elevation 750 ft., 2) attenuation due to the reservoir's size as a function of gate openings under the existing rule curve and, 3) deliberate operation within the operating envelope of the existing rule curve. Table 1 lists those storms before which significant storage existed to reduce releases so that flow in the river below the dam at Solvang was less than 20,000 cfs. Based on the record since construction of the dam, (1955-98), available storage was sufficient to significantly reduce releases in seven of 14 (50 percent) large storm events. (The analyses in Section 4.0 of this memorandum focus on reductions possible by operations which are not within the rule curve.)

3.0 FLOOD CONTROL DISTRICT: MONITORING AND PREDICTION

In order to provide the highest measure of public information and response to significant storm events, the Santa Barbara County Flood Control and Water Conservation District has developed and maintains rainfall and streamflow monitoring capability. In addition, Flood Control has developed partnerships with other agencies such as the National Weather Service for rainfall forecasting. The district has upgraded and improved its capability as technical improvements have become available. The current systems are discussed below.

3.1 Weather Prediction

Flood Control relies on two outside sources of weather forecasting: the National Weather Service and private consultants. Through an existing agreement, the NWS provides not only typical weather forecasts, but quantitative precipitation forecasts (QPF) for each significant storm which may affect the county. The NWS provides QPF for specific locations which are considered important to predicting storm runoff effects, including Gibraltar Reservoir, Santa Maria and Santa Barbara. The Gibraltar Reservoir QPF is utilized in the FCRIVER model predictive mode as the basis for estimating storm runoff before the onset of rain. Both Flood Control and the NWS monitor Flood Control's ALERT gage system to update predictions throughout significant storm events.

In addition to the NWS predictions, Flood Control obtains predictions from private weather consultants throughout the wet season. Currently, Pacific Weather Analysis provides weather synopsis and forecast to Flood Control for each storm event. These predictions are also used by Flood Control to estimate storm effects based on the FCRIVER model. When significant differences between available predictions arise, Flood Control staff evaluates the information available to develop an appropriate set of prediction data.

3.2 ALERT System

Flood Control participates in a cooperative data gathering and transmission program called the "ALERT System" (automated local evaluation in real time). The system is a series of remote radio communication devices which transmit data from automatic rain gages and streamflow gages to Flood Control and the NWS. The communication devices and data transmission are standardized so as to allow interconnection and data sharing among system users. ALERT System devices located in the Santa Ynez River watershed are shown on Figure 7. The ALERT System is supported by backup power generation and computing systems.

ALERT System software allows data to be easily stored and retrieved. The form of the data stored by Flood Control is deliberately made compatible with input needs of the FCRIVER model. Thus rainfall and stream flow data can be compiled, and are formatted to support real-time modeling runs of FCRIVER during storm events with minimal additional effort.

3.3 Rain gage network

Flood Control maintains a system of gages located to provide representative rainfall data throughout the County and in adjacent contributing watersheds. The rainfall gages collect data continuously and are connected to the ALERT System. Depending on the specific equipment at a particular site, rainfall is reported at specific time intervals or at specified increments of rainfall. The system is equipped with alarms which indicate high intensity events. A description of the equipment located at each site and its operation is contained in Flood Control's report "Santa Barbara County Rainfall 1996-1997". Complete rainfall records are available from Flood Control; a summary is in the report.

3.4 Stream gage network

Flood Control, the Water Agency, the City of Santa Barbara, the Montecito Water District, and the USGS operate and maintain a system of stream gaging stations in the Santa Ynez River watershed. Several of these stations are part of the ALERT System and provide the basis for stream flow data during storm events. Stream gage data are reported to the ALERT System on 15 minute intervals. The gages actually measure water elevation and require rating tables to convert measurements to stream flow. The river channel downstream of Cachuma Reservoir is subject to aggradation and degradation as flow conditions change; because of changes to the stream channel, high flow rating curves for these gages must be calibrated by actual measurement during periods of peak flow. (Thus peak flow measurements are considered only estimates until calibration calculations are made, generally after the storm event.) However even without the calibration, the calculated peak flows generally vary only 10 to 15 percent and thus are adequate for storm monitoring and making operational decisions for Bradbury Dam. Since inflow to Lake Cachuma is based on change in storage, calculation of inflow rate is not subject to rating curve calibration.

3.5 FCRIVER Model

Flood Control developed a predictive tool for forecasting flood flows on the Santa Ynez River after substantial property damage occurred in 1969. As data and software have allowed, Flood Control has updated the model to improve its accuracy and ease of use. In the fall of 1997, the model was modified to allow straightforward representation of modified operations (operations which deviate from the existing rule curve). The development and operation of the model are discussed below. The current form of the model was documented by Flood Control in 1991. (The documentation may be reviewed at the offices of Flood Control.)

3.5.1 Basis and development

FCRIVER is a numerical simulation of the storm runoff and reservoir operation in the Santa Ynez River watershed. It is a 96-hour model with hourly time steps. It consists of a main program and several subprograms which are "called" from the main program and the "hydrograph sub-program".

FCRIVER generates runoff hydrographs for sub-watersheds, using the standard unit hydrograph procedure to distribute rainfall excess (runoff) for one hour time periods during and following a storm. The amount of rain which runs off is calculated using Antecedent Index (AI) procedures, which estimate the ability of pervious area soils to accept rainfall with the excess being runoff. The procedure for calculating AI accounts for changing sun angle, and hence varying potential evaporation, through the seasons of the year. Initial AI values for key stations are determined by Flood Control, and are input to the model.

Predicted rainfall at Gibraltar Dam for one hour time increments is input when a run is to be based on a quantitative precipitation forecast (QPF). (If the model is run in predictive mode the single value of predicted hourly rainfall for Gibraltar is distributed throughout the watershed to account for "typical" storm movement and orographic effects.) Hourly rainfall amounts for several rain gages are input to the program when a run is to be made based on observed (actual) rainfall.

The initial base flow in the river at Gibraltar is required input. Watershed areas, path lengths, elevation changes (and thus lag times), rainfall as a function of gage location and watershed conditions to be used are fixed or are calculated by the program.

The runoff hydrographs are routed through Gibraltar and Cachuma Reservoirs, routed down the Santa Ynez River, and added (combined) with tributaries' contribution as required to generate complete hydrographs at various points along the river. Reservoir routing is a trial and error storage method procedure based on the basic hydrologic equation:

Change in Storage=Inflow - Outflow.

Storage volume data and functions to determine spillway gate openings and discharges are based on lake levels, as are rain on the lake calculations. The user must supply the initial lake reservoir elevations, and may modify Cachuma gate operations if desired. Channel routing is by standard Muskingum method. The travel times through reaches and translation factors are built into the program and do not require user input. Hydrographs are added by summing the rows of columns in the flow array corresponding to the hydrographs to be added.

3.5.2 Operation of model

In order to run the FCRIVER model, several key parameters must be entered:

- Date and time of beginning of storm precipitation,
- AI values for Gibraltar Dam, Figueroa Mountain and Lompoc,
- Elevation of Gibraltar and Cachuma Reservoir at "time 0", e.g. at the initial time step,
- Flow in the Santa Ynez river at Gibraltar Reservoir at the initial time step, and
- Hourly Rainfall either as:
  Distributed quantitative precipitation forecast values for the mountain areas, or
  Hourly precipitation values at six rain gages.

The model is menu driven and prompts for these parameters. The model output may be printed as hydrographs or in tabular format. In "default" mode the model utilizes the existing Cachuma Reservoir rule curve to calculate gate opening (in response to reservoir elevation during a spill) and discharge.

The model may be run with predicted rainfall (QPF) and under these circumstances the model distributes the QPF estimates geographically. (Since QPF data are provided in six hour increments, the QPF data are distributed in one hour time increments for use by the model.) The model may be run with actual rainfall data in which case the model requires hourly data from six gages distributed throughout the watershed. These gages are part of Flood Control's ALERT System. Data from these gages are regularly telemetered to Flood Control's Santa Barbara office year round.

The model may be run with both predicted rainfall data and actual rainfall data. In that case the model allows successive hours of actual rainfall data to be substituted for the predictive (QPF) data. This feature allows direct comparison as the storm occurs between the conditions from predicted rainfall and conditions expected from actual rainfall.

Evaluation of Modified Operations

If the model is to be run to analyze modified storm operations three additional values must be provided: "Prelev", "Maxprel", and "Gatehold". First, a value for the elevation at which pre-releases start (or are increased) "Prelev" must be input (This is the elevation to which the lake is drawn down if precautionary releases are made.) At this elevation the model provides releases based on calculated inflow to the reservoir during the previous hour. This causes modeled releases earlier and greater in volume than called for under the rule curve. (These are releases of early storm runoff or "prereleases".) In addition, a value must be specified as the maximum rate of pre-releases called "Maxprel". Once the inflow reaches that specified maximum rate (Maxprel) the model holds the release rate constant while allowing the lake to rise until the operational rule curve is reached and so long as inflow is greater than releases. Finally the model will accept a value for "Gatehold", the gate opening distance (arc opening) in feet at which the lake is allowed to rise (or surcharge) against the gates above the level stipulated by the rule curve, but no less than 1.0 foot from the top of the splashboard at all times.

3.5.3 Accuracy of results

Flood Control has utilized the FCRIVER model extensively since its development in 1979. Significant storms occurred under wet watershed conditions in 1980, 1983, 1986, 1991, 1992, 1993, 1995, and 1998. Flood Controls comparison of model results against actual (measured) streamflow suggests the model is accurate to within 10% in its prediction of peak flows for a wide range of large and moderate storms. In smaller storm events, or in events where a significant amount of upper watershed precipitation occurs as snow, the predicted peak flow may vary from the actual flow by significantly more than 10%. In addition, under some rainfall distribution conditions, the model gives results which indicate a slightly longer peak flow (duration) with lower amplitude (maximum) but with the same volume as the peak period of flow as compared to measured flow.

3.5.4 Treatment of modified Bradbury Dam operations

Recent modification of the model to facilitate analysis of modified operation of Cachuma Reservoir consists of changes to represent deviation from the standard rule curve. Rather than a treatment of the spillway gate opening based only on the rule curve, the model allows modification of the parameters which control gate openings (so as to simulate precautionary releases, early releases of storm flow, and gateholding). Modeling of other hydrologic parameters has not been changed. The model allows stipulating initiation of releases below elevation 750 ft., "Prelev". As noted above, the model allows establishing a maximum rate for prereleases "Maxprel". Finally the model allows identifying a gate opening distance at which the lake level is allowed to rise against the gates (which are held at a constant opening "Gatehold". Each of these parameters is discussed below.

The model provides that the elevation at which pre-releases start (or are increased) "Prelev" may be set below elevation 750 ft., the point above which the gates normally begin to open. At this elevation the model provides releases based on calculated inflow to the reservoir during the previous hour. This causes modeled releases earlier and greater in volume than called for under the rule curve.

In addition, when simulating a release of early storm runoff, the model requires a value be specified as the maximum rate of pre-releases, "Maxprel". Once the inflow reaches that specified maximum rate the model holds the release rate constant while allowing the lake to rise until the standard operating rule curve is reached and so long as inflow is greater than releases.

Finally the model will accept a value for "Gatehold", the distance (gate arc opening) in feet at which the lake is allowed to rise against the gates (above the level stipulated by the rule curve). In essence, the gates are held at a constant opening while the lake is allowed to rise within 1.0 foot of the top of the splashboards. For this calculation, current hour lake level rise is used. If the lake level is calculated to rise within 1.0 foot of the top of the splashboards, the model opens the gate at least 0.1 ft (in 0.1 ft increments) to keep the lake 1.0 foot or more from the top of the splashboards at all times.

In order to most effectively manage Bradbury Dam operations in response to a significant storm, the FCRIVER model should be run before, and during the storm. Emphasis should be on proper interpretation of modeling results as representing watershed response to first predicted, then actual rainfall. Model predictions should be used to test a range of management options and their benefits. Specifically, key actions such as precautionary releases, early storm runoff releases and gateholding should be tested and the efficacy of the next decision to be made (action to be taken) evaluated. For example, if during the early phases of a storm, rainfall in excess of the QPF occurs in the lower portions of the watershed, the model should be utilized to evaluate whether the maximum early release rate (Maxprel) is appropriate given existing channel capacity and predicted flow. A more complete discussion of the use of FCRIVER during modified operations is provided in Section 4.4.

4.0 MODIFICATION OF OPERATIONS

Operational modifications of the existing reservoir can produce substantial reductions in downstream flows for storms of moderate to fairly large magnitude where pre-storm reservoir storage is at or near full. The intent of modified operations is to move water through the release works (and past the flow sensitive areas downstream) before or after the anticipated peak inflow. Three operation changes may be employed individually or in concert:

1. pre-storm reservoir drawdown of up to several feet, or "precautionary releases";
2. release of storm inflows up to a calculated maximum flow while holding reservoir below normal operational level, "prereleases"; and
3. after lake reaches above-full condition, hold spillway gates to achieve extra reservoir surcharge, "gateholding".

The first two operational changes move water through the reservoir before the peak inflow, the third holds water in the reservoir for release after peak inflow. Each of these techniques is discussed below, followed by a discussion of their integration to accomplish maximum reduction of peak releases. The effect of these techniques individually and in concert are shown in Table 2 for the February 23-24, 1998 storm.

4.1 Reservoir Drawdown Below Elevation 750 ft. (Precautionary Releases)

Temporary evacuation of water to lower the lake elevation a few feet provides storage for initial detention of runoff from the expected storm. This allows subsequent runoff to occupy that space thus keeping reservoir water level from rising as much during the early part of the storm. Used in concert with releases of initial storm runoff ("prereleases"), maximum lake level rise during the storm runoff event (thus gate opening) can be reduced.

4.1.1 Effect on storm routing

The effects on storm routing are due to additional storage being available before a spill is initiated. The effects are to delay peak releases and to reduce the peak releases. The magnitude of these effects is a function of the ratio of storm runoff (particularly the volume before peak reservoir inflow) and the volume evacuated. If the volume evacuated is small in relationship to the volume of runoff, the effect of the evacuation will be small. However, by increasing the release rate of initial storm runoff, this effect can be increased somewhat, as discussed in section 4.2, below.

4.1.2 Means to achieve lower reservoir level (watershed condition and timing)

Precautionary releases may be initiated within a fairly short time frame before a storm event (a day or less). However, the shorter the time available to evacuate space the higher the rate of releases required. At elevation 750 ft., the lake surface is approximately 3,000 acres. Thus 3,000 acre feet of storage is made available for each foot of evacuated space. Depending on the size of the anticipated storm, the rate of existing inflow, and the time available to accomplish the evacuation, the release rate could be relatively high. Downstream conditions such as existing flow and channel capacity must be considered when releases are planned. The formula for generation of estimated release rates necessary for a given time to achieve large volumes of evacuation:

Acre feet evacuated = (release rate - inflow<in cfs>) x 1.983 x (hours of release/24)

The time available to accomplish the desired amount of drawdown will be dependent upon meteorological forecasting of the expected large storm event. This period is usually a day or more in length. Although long term forecasts are becoming more reliable, the ability to draw down the reservoir adequately in 24 to 36 hours suggests that long term (three days or longer) forecasts need not be the basis for lowering the reservoir, nor should they be.

For example, a foot of drawdown (a volume of 3,000 AF) may be achieved in one day by insuring that reservoir outflow exceeds inflow by about 1,500 cfs. for 24 hours To put this in perspective, if lake inflow is 2,500 cfs and downstream flows of up to 10,000 cfs are deemed acceptable during the time of the proposed evacuation, releases may be made at a rate up to 10,000 cfs so that outflow may exceed inflow by as much as 7,500 cfs. If releases exceed inflow by 7,500 cfs for 24 hours, such releases would result in 15,200 acre feet of evacuation or 5.1 feet of drawdown.

This example is described below as a part of modified storm operations. If a large storm event is expected to reach the watershed in about one and one half days, releases could be increased to 10,000 cfs, and after 24 hours the release reduced from 10,000 cfs back down to the computed inflow level (now somewhat less than 2,200 cfs due to normal flow recession on the watershed). Under these circumstances the one day drawdown could have increased the reservoir storage by about 15,200 acre feet (which corresponds to a little over 5.1 feet of lake lowering). The lake may be held at this level in preparation for the expected storm event with minimal contribution to downstream flows. Such a release of water can be done without loss of Cachuma Project water because analysis of watershed conditions indicated that expected lake inflow, absent any further seasonal rainfall, would be over 25,000 acre feet.

In order to protect water supplies, this modification should only be implemented when inflow is occurring and sufficient future inflow is estimated to occur such that future inflow will replace the precautionary release in the same wet season. Future reservoir inflow from previous rainfall may be estimated as a function of declining runoff or increasing antecedent index. Thus as discussed in the next section, it is possible to provide for meaningful precautionary releases and still assure that a spill condition is reached later in the same year.

4.1.3 Risk to water supply

Releasing water from Lake Cachuma could affect water supply if an equivalent volume of water is not conserved, up to the limit of the reservoir's conservation pool. That is, if 6,000 acre feet of water is released and no additional water flows into the reservoir, 6,000 acre feet would potentially be lost to supply. However if the lake receives 6,000 acre feet of runoff and spills later in the season, no water supply is lost. As a practical matter, the conditions under which precautionary releases are recommended mean that the reservoir is full, or nearly so, and that runoff is occurring. Using historic response of the watershed as a model, future runoff can be estimated.

Specifically, estimates of future inflow can be used to define the maximum pre-storm reservoir drawdown possible without jeopardizing Cachuma Member Units' water supplies. The volume of flow remaining to run off into the reservoir may be estimated based on a "curve fit" between historic runoff curves and existing runoff conditions. Key match components are current rate of runoff and "shape" of the recession curve. Recession curves relating reservoir inflow to time are asymptotic to a semi-logarithmic function. After several weeks, daily inflow plotted on a semi log plot is between 0.95 and 0.97 of the previous day's flow. *(The formula is: Cachuma inflow on any day(n+1) is equal to inflow of the previous day(n) multiplied by a recession factor.)* The area under the curve is a measure of water that is yet to flow into the reservoir.

From a practical standpoint, the estimation of future reservoir inflow is carried out by matching the daily reservoir inflows going back to the last storm daily inflow peak with one or more "typical" daily recession curves based on previous observations of recession on the Cachuma watershed. The match also includes selection of the initial (non-asymptotic) portion of the recession curve (Figure 8). Actual daily flow values since the previous storm peak flow are plotted on a graph with the same dimensions as Figure 8. The plot is then superimposed over the "typical" recession graph by sliding back and forth along the X-axis. (To be valid, the Y-axis scales must match.) When an acceptable match between actual and typical graphs is found, then future inflow may be predicted from the "typical" recession graph.

For only modestly wet conditions this maximum recession value (of the "straight line" portion) is .95 (Gibraltar seasonal rainfall to date less than 25 inches); for very wet conditions (Gibraltar rainfall more than 50 inches) a maximum value of .97 should be used. Once the daily recession coefficient reaches this maximum level, the entire mass of future reservoir seasonal inflow, assuming no further rainfall, may be calculated using the summation formula for an infinite geometric progression, $S = A/(1-R)$, where S is the sum total of all future inflow, A is the reservoir inflow on the day that the recession coefficient reaches its maximum value, and R is the maximum value for the recession coefficient.

An accurate estimate of future reservoir inflow requires knowledge of the technique and its limitations. Key considerations include: 1) time since last storm peak inflow; 2) time of the day of the actual hourly peak occurrence; 3) occurrence of even small amounts of rain during days after the main event; 4) antecedent conditions before the last storm; and 5) timing of any "non-normal" releases made from Gibraltar Dam since the last storm. These, and other considerations, such as typical "noise" in the plot of inflow the first few days after the previous storm event (variation from the "ideal" smooth curve) may affect any estimates. Thus making conservative assumptions as the basis of any pre storm precautionary releases is appropriate. Based on experience of the Water Agency staff, we recommend that initially 50% of the of the estimated future runoff be considered the maximum prestorm evacuation volume. We anticipate that additional experience and development of the technique of estimating future runoff may allow increasing the percentage of maximum lowering to 2\3 or 3\4 of the runoff remaining. For example, AI (antecedent index) as a measure of watershed wetness, and indirectly remaining runoff, may allow a second method of determination of maximum evacuation.

4.2 Early Releases of Storm Inflow from Rainfall in Upper Watershed

This operation may be undertaken with or without any pre-storm reservoir drawdown below the 750 feet, MSL full elevation (precautionary releases). The concept of this second procedure is routing early storm runoff more quickly through the reservoir so as to reduce the maximum lake level during peak storm inflow, thus reducing peak storm release. This operational modification releases water at a rate greater than the historic rule curve during early phases of storm runoff and must be limited by accurate knowledge of downstream channel capacity and flow conditions. Since the release rate is determined from measurements of actual rainfall, there would be no risk to water supply from this modification.

4.2.1 Effect on storm routing

Releasing early storm releases allows disposal of part of the runoff from the storm event while holding the reservoir to very small elevation increases. This preserves more reservoir space to be used as flood detention storage (including lake surcharge space above elevation 750 ft,) during the highest inflow hours of the storm. The procedures used in February 1998 established a maximum pre-release rate limited to flows which, when routed to Lompoc Valley with below Cachuma tributary inflow, would not produce significant additional flooding impact beyond that which would occur from flows to be expected under operations under the original rule curve. Staff recommends that channel capacity and flow magnitude at Solvang be considered as well.

4.2.2 Basis for initiating and limitation of peak release of early storm inflow

The technique relies on accurate and current rainfall data from key areas in the watershed, and accurate measurement of inflow to Lake Cachuma. The model is run in predictive mode before the storm and also with actual rainfall data to first establish the maximum release rate, and second to confirm downstream flow conditions. The implementation procedure requires calculating reservoir inflow each hour, and adjusting the spillway gates to release water at the rate of the last hour's calculated inflow. Adjustments are made every hour until the release rate equals an agreed upon maximum rate for the forecast storm event, "Maxprel". The spillway gate openings are then held constant until the reservoir water surface rises to the point where the suggested gate openings, using the original gate opening vs. lake elevation rule curve, equal the existing gate openings from the release of early storm inflow explained above. As the lake continues to rise, the gates are opened pursuant to the standard opening vs. reservoir elevation rule curve. During all these gate adjustments, it is understood that spillway operations require all four gate openings to be equal.

The maximum early inflow release rate for each particular storm is based on the capacity of the downstream channel and an estimate of the rate of release necessary to reduce peak storm releases. Both considerations should be evaluated in consultation with Flood Control based on the condition of the lower river, the overall condition of the watershed and the nature and predicted intensity of the approaching storm. It is recommended that the maximum releases of early storm runoff be reevaluated as the storm develops and will be modified as revised estimates of downstream tributary inflow are available. As discussed in the next section, this is especially important if rainfall in the lower watershed substantially exceeds the QPF in intensity or total rainfall.

4.2.3 Effects on flow downstream

If the maximum early storm releases (Maxprel) are too large, flow in the lower river may not be reduced to the maximum extent practical. Careful monitoring of storm rainfall measured by Flood Control's ALERT System and reevaluation based on updated runs of the FCRIVER model will avoid the risk of releases of early storm runoff which are too large. This is because the lower watershed responds to rainfall events sooner than the upper watershed. Thus the effects of more intense or larger amounts of rainfall (than initially predicted) can be evaluated before releases approaching the maximum release rate are made. Conversely, if early storm releases are too small, the lake level will be higher than optimal for subsequent operations such as gateholding, and the reduction of the peak releases will not be as great as possible. In both circumstances, early storm releases too great or not great enough, peak releases would be less than under the present rule curve and thus downstream flow reductions would still benefit landowners below the dam.

By making early storm releases dependent on the previous hour inflow to the reservoir, releases due to a storm which is smaller than initially predicted will remain less than the magnitude of the flow generated in the absence of the Cachuma Project. Furthermore, the timing of response to rainfall in the lower watershed compared to the upper watershed further reduces the peak flow in storms which are not as large or as intense as predicted. (In storms which are smaller than predicted, "Maxprel" may not be reached.)

4.3 Temporary Surcharge (Gateholding)

Gate design and operation at Bradbury Dam allow surcharge of the reservoir. That means that the reservoir level can be controlled so that water level may be raised above the normal operation level at any gate opening (release rate) without overtopping the release works or embankment. This allows releases to be held significantly below inflow during the period of peak inflow. In conjunction with lake level lowering and early runoff releases, gateholding will maximize the size of the reduction of downstream flow. Since this operational modification occurs during a spill condition, there is no risk to water supply.

4.3.1 Effect on storm routing

Gateholding retards the storm peak through temporary surcharge of the reservoir. By holding the gates at a lower (smaller) opening, the peak release is reduced. The effect on downstream flow is to 1) reduce peak releases and to 2) prolong the maximum releases. The same volume of water ultimately passes through the reservoir and its release works.

4.3.2 Method and limitations

The third modification of Bradbury Dam and Cachuma Reservoir storm operations involves taking advantage of the extra height of the spillway gates to allow smaller openings than under the standard gate opening vs. lake elevation rule curve. This modification is implemented when the gate opening, operating on the standard rule curve, is greater than or equal to the opening fixed as a result of storm pre-release operations (if any).

The effect of this operation (gate holding) is to provide additional flood detention storage. Modeling suggests that adequate space exists for storms up to and somewhat larger than the magnitude of the very large January 1969 event. Potential limitations of this technique are discussed in Section 4.4.

Gate holding utilizes the fact that during storms, the top of gate level rises at a greater rate than the lake level. Thus, under the standard rule curve, at a lake elevation of 750 feet, MSL the top of gate (closed) elevation is 751 feet while at lake elevation of 752 feet, top of the splashboard is at 756.6 feet. This relationship is shown on Figures 1 and 2.

Under this modified operation, the lake elevation is allowed to rise to a determined elevation (corresponding to a specified rate of release) and then the gates are held at a constant opening while the water is allowed to rise. When the water rises to within 1.0 foot of the top of the splashboards, the gates are opened further (in 0.1 ft increments), depending on calculated inflow rate. This process of inching the reservoir gates open in a surcharged condition is continued until the reservoir elevation stops rising. The reservoir is allowed to drop at the last gate opening until the standard rule curve relationship between lake elevation and gate opening is reached. This process keeps the gate opening (thus flow) as small as possible throughout the highest inflow thus reducing peak downstream releases. Up to 1.0 ft of gate freeboard is maintained at all times.

For very large storms, such as those larger than the January 1969 event, the operation would smoothly transition to an increased rate of gate opening vs. lake elevation change, such that the reservoir would safely pass (with 5 to 6 feet of embankment freeboard) the original spillway design flood. It should be noted here, based upon a 1994 Reclamation Paleo Flood Study, that the January 1969 event was found to have produced the largest flow in the Santa Ynez River between Cachuma and Lompoc in 2,900 years. In a revised flood frequency chart prepared by the Bureau geologists, the January 1969 flood was given a frequency of recurrence of once in 1,400 years. (Based on the analyses in this memorandum, it may be appropriate to revise the rule curve to stipulate lower gate openings vs. lake elevations than the existing curve up to perhaps the 756 ft, MSL, and then transition into larger gate openings than the standard curve for lake elevations above that level.)

4.3.3 Risk to spillway operability

Gateholding reduces the freeboard of the gates during significant inflow and when the level of the reservoir is rising. Under these circumstances, there is a higher probability that the water level could exceed the top of the gates, allowing water to spill over the top of the gates. The design of the gates does not provide for spillage over the top. Thus some damage could occur if the rate of flow over the top of the gates was large and/or of long duration. In order to better understand risks associated with overtopping, an evaluation of potential damage to the structure of the gates may be appropriate.

Recent modifications to the gates associated with seismic retrofit have made the gates completely reliant on electric motors for opening. These motors are powered by the local grid. Because it is possible for that source of electricity to fail during storm events, Reclamation has provided backup electrical generation capacity. The adequacy of this backup power is essential for both standard operations and modified operations, particularly gateholding.

4.4 Integration of operational modifications

The three elements of modified operations discussed above exhibit synergy; they are more effective in reducing peak outflow when used together during the same storm than if used only singly or two together. Physically these modifications reduce peak downstream flows by temporarily storing peak inflow in the reservoir and releasing it at a reduced rate. Precautionary releases and release of early storm inflow make additional storage available by moving water through the reservoir before the peak storm inflow. (This is accomplished by releasing water before and at greater rates than required by the original rule curve.) Gateholding reduces and retards releases during peak inflow. Each of these techniques performed alone will reduce peak storm release. However performed together, the reduction of peak release is greater than simply adding the expected effects together because each technique allows the subsequent operation to start at a lower lake level.

An analysis of the February 23, 1998 storm shows the potential reduction of peak releases under each modification and also if the modifications are performed together. This analysis uses the FCRIVER model with the same rainfall conditions and antecedent index as Figure 6 (discussed in Section 2.3). However modified storm operations were assumed: the reservoir was drawn down, early storm runoff was released, and the reservoir was allowed to surcharge during peak inflow (gate openings were held constant, see Figure 12). As is shown in Table 2, these modified operations reduced flows in the Lompoc area approximately 40% as compared with no modifications, and reduced flows by 10% compared to the sum of the reductions applied each separately.

4.4.1 Utilization of weather predictions (QPF)

Weather predictions indicating quantity and intensity of rainfall QPF, can be evaluated using the FCRIVER model to determine whether a storm is a candidate for modified operations given existing watershed conditions, reservoir storage and channel capacity. Normally if a storm will result in less than 20,000 cfs peak release from Cachuma Reservoir, it would not warrant modified operations. Table 1 lists historic storms which could have resulted in such releases.

Often several different forecasts will be available for each approaching storm. Since the FCRIVER model may be easily run, various forecasts may be evaluated to determine the range of potential stream flow conditions and to assess risks associated with the more extreme predictions.

4.4.2 Role of the FCRIVER model

The FCRIVER model may be used to evaluate and compare alternative operational strategies. Although the model has been utilized extensively and its results are believed accurate, interpretation of model run results by an experienced hydrologist or engineer is critical. In order for input data to result in valid results, several issues must be evaluated. First, it is usual to receive a range of QPF estimates from various credible sources. Selection of input data for initial model runs must consider the sources of data, the overall condition of the watershed and the sensitivity of results to different estimates. Often, multiple runs will be appropriate.

Second, the identification of potentially damaging storms does not necessarily mean that modified operations are appropriate. The identification of candidate storms must include consideration of the flexibility of the modified operations so as to develop a strategy that protects water supply while allowing effective reduction of downstream flows.

During actual storm events, regular model runs substituting actual data for QPF data should be performed. The model results from various runs must be evaluated to understand the effect of actual rainfall compared to QPF values initially used. The key question to be considered is: what changes, if any, need to be made to the initial operations modification strategy to best protect water supply while reducing downstream flow given actual rainfall.

Experience is crucial to recognize and interpret several key variables:

- freezing level (causing precipitation as snow at higher elevations),
- difference between predicted and reported streamflow (including downstream tributaries), and
- timing of actual peak inflow and initiation of gateholding.

Since natural systems rarely perform as predicted, it is important to consider how to modify the operational strategy if the storm is smaller or is much longer in duration. Keeping in mind specific responses will reduce the potential for error. Thus all decisions should include consideration of model runs which test the system's sensitivity to variation from predicted conditions.

Since the FCRIVER model can generate a large amount of information very quickly, some protocol for recording key attributes of important model runs and interpretation of results may prove necessary. An outline of suggested protocol issues is included as Section 5.0 of this report. Upon direction, Water Agency staff will develop this section in cooperation with Reclamation, the Member Units and downstream interests.

4.4.3 Predictive vs. real time modeling

The principle difference between the FCRIVER model run in predictive mode and run with actual rainfall data is how rainfall is distributed temporally and spatially within the watershed. In predictive mode the model accepts a single QPF value for the Gibraltar Reservoir area and distributes the rainfall spatially based on historic data. The model distributes the QPF (typically provided in six hour time increments) one hour increments reflecting "typical" storm movement and orographic effects.. As actual rainfall data are substituted, more precise distribution of rainfall in time and space becomes known. Concentration of rainfall in time and/or in specific areas in the watershed may cause significant changes in predicted runoff and must be interpreted based on the changes in timing and geographic distribution data, not necessarily in changes to the more general QPF input values.

Thus as any significant storm event occurs, the FCRIVER model should be run with actual rainfall data as they become available. Timing and intensity of rainfall should be compared to original predictions to evaluate changes in predicted runoff, and the possible need to change reservoir operations.

4.4.4 Limitations to the techniques

Several limitations to the modified operations exist. These limitations are due to the risk of loss of water supply or damage to the reservoir facilities if the modified operations are not implemented properly. The original rule curve was based on observations and operations under direct control of the operators at Bradbury Dam. The modified operations rely on data and analyses which may not always be available to the dam operators or which may be beyond their area of expertise to interpret. Analyses, particularly weather predictions such as QPF forecasts, have uncertainty and actual conditions may not be even close to those predicted. In addition, the operations require that the gate of the reservoir be operated in a different manner and may require different emergency response in the event of power failure or communications breakdown. Each of these factors suggests that the modified operations be implemented with these limitations in mind.

- QPF and the model use of QPF

Determining the storms which are candidates for modified operations and the development of an initial strategy depend on watershed conditions and storm quantitative precipitation forecasts(QPF). Watershed conditions are closely monitored and generally well known. Weather predictions, particularly QPF, are not precise, and at times not accurate. Although most forecasts tend to be conservative, that is they over-predict precipitation, under-prediction often occurs. Flood Control typically have available three of four QPF forecasts from the National Weather Service, commercial forecasting companies, and its own staff. Since the FCRIVER model may be run easily with different data sets, evaluating the range of potential storm impacts and developing strategies to respond to the range of potential conditions can be done prior to the onset of precipitation. Closely monitoring the development of the storm as it approaches the Santa Ynez Watershed will allow timely evaluation of changing conditions and implementation of revised modifications to reservoir operations.

- FCRIVER model transition from QPF to actual rainfall data

In "predictive" mode the FCRIVER model accepts precipitation data for a single location (Gibraltar) and determines subwatershed precipitation based on assumed "typical" conditions in the rest of the watershed. Because the specific storm may spread precipitation across the watershed in a manner very different from the model and forecast assumptions, modifying inputs during the actual storm is essential. When modified operations are implemented, the model should be run with updated precipitation data virtually on an hour by hour basis as the storm develops. Both the differences between the QPF and the actual rainfall data at Gibraltar as well as the rainfall distribution through the watershed should be assessed. The modified operations developed for the storm should be evaluated and changes to ongoing operations assessed.

- Experience of modeler, input and interpretation of results

While the FCRIVER model is a useful tool for flow prediction, its results must be interpreted based on knowledge of the watershed. For example in cold storms (where freezing level is below 5000 ft elevation,) significant precipitation may fall as snow in the upper elevations. Peak storm runoff may be significantly reduced as a result. Storms which pass over the watershed more slowly or more rapidly than anticipated, or which develop highly productive cells of precipitation may cause substantial deviation from predicted flow conditions. Those involved in evaluating modified operations must have the experience to recognize and interpret these types of variations as they are reported through the ALERT System.

- Risk to water supply

Cachuma is the largest single source of water to the southern and central portion of Santa Barbara County. Both precautionary releases and early storm runoff releases have the potential to reduce water supplies if rainfall is not sufficient to replace the volume of water released. This risk is greatest when the watershed is not in a wet condition (when AI is moderate or high). These conditions are typical before major storms have saturated the watershed and also suggest that the runoff from a single storm would be only a modest percentage of precipitation. Thus early season storms may not be good candidates for precautionary releases, particularly if the AI is high.

In addition, in early storms, effective reduction of releases may be achieved with gateholding only. Or in other circumstances, early storm releases may be started later than if the watershed was wet, and the results of actual storm runoff allowed to determine the need for and the rate of increase in releases.

- Backup electrical power

The spillway gates rely on electrical power to open. Some form of backup power has been available at the dam in the case of failure of the local supply. If the gates cannot be opened under conditions of a rising lake, overtopping of the gates would be a risk. Damage to the gates due to overtopping may occur if the volume of the water spilling over the gates carries enough force to break welds in or bend the gates support structures. Due to the occasional long periods when the gates are operated (and indeed the system can be tested under wet conditions) additional backup generation capacity appears warranted. Since the gateholding procedure results in less freeboard, rapid access to an on-site backup power source to auxiliary power may be necessary.

- Access to data and modeling: communications

The modified operations rely on rainfall data from the ALERT System and the FCRIVER model to evaluate changing storm conditions. Communications from ALERT raingages and among Flood Control and Reclamation operations personnel are essential or no good basis would exist for operational modifications. Both Reclamation and Flood Control have redundant communications systems. In addition, several more raingage stations are on the ALERT System than are utilized by the model. However, the modified operations are vulnerable to loss of communications until some or all of the operations can be described in a 'rule curve " format which relies only on information available to the dam operations personnel.

4.4.5 Fallback in the event of system failure

In the event that dam operators do not have access to rainfall data or modeling evaluations for a significant period of time, it is suggested that Reclamation rely on previous hour lake inflow as the basis for release setting until "Maxprel" is reached, then utilize the rule curve if sufficient communications have not been reestablished. If in gateholding mode, Reclamation may consider adjusting gates every 0.1 ft with a minimum freeboard of 1.0 ft until lake level is at or above 755 (or transitioning to the rule curve on a sliding scale which increases freeboard) until communications are reestablished.

5.0 PROPOSED STORM OPERATION PROTOCOL

Protocol for communications and decisionmaking has been discussed by involved agencies and was implemented on an informal basis during February 1998 storms. This section outlines a proposed protocol based on what was learned in those discussions and during actual operations. Included are proposed methods for interagency contacts (Figure 13), consultation for significant storm events, gathering and sharing data, responsibility for modeling and reservoir operations as well as determining watershed conditions and estimating water remaining to runoff from the watershed.

5.1 Interagency Contacts

In each of the three phases of the modified operations clear expectations regarding communications must be met. Evaluation and decisions-making responsibilities are shared by Flood Control and Reclamation. While other agencies need to be kept informed, the focus of the communications during modified operations must remain on storm monitoring and evaluation. Figure 13 shows the basic lines of communication for modified operations.

- Flood Control will monitor approaching storms and will contact Reclamation regarding any that warrant consideration for modified operations. Communications should be between identified representatives using telephone or, as backup, radio systems. Communications to SYRWCD (Santa Ynez River Water Conservation District), COMB (Cachuma Operations and Maintenance Board) and City of Lompoc as to modified operations will be by telephone or "fax" and may consist of messages.
- During storm events, Flood Control and Reclamation will communicate hourly (as ALERT data allow revised modeling) until peak storm inflow has passed or modified operations are no longer needed. Communications should be by telephone or radio. Significant changes in operations will be communicated to SYRWCD, COMB and Lompoc will be by telephone or fax and may consist of messages.
- After any storm during which modified operations were employed, Reclamation and Flood Control will prepare brief storm operations summary. The summary will be circulated to SYRWCD, COMB and Lompoc when complete.

5.2 Prestorm Consultation

Prestorm consultation will be between Flood Control and Reclamation. Flood Control will evaluate approaching storms and identify those which are of potential concern. Based on their evaluation Flood Control may contact Reclamation by telephone or radio to discuss the efficacy of modified operations. Such communications will be between the designated contacts for each agency. Decisions regarding modified operations will be forwarded to SYRWCD, COMB and Lompoc by telephone or fax.

5.2.1 Watershed condition and reservoir status

Flood Control and Reclamation will consider watershed conditions, status of reservoirs on the river (particularly water expected to run off into Cachuma Reservoir), channel capacity and potential tributary runoff as part of their consideration of modified operations. Flood Control and Reclamation will include in these evaluations:

- downstream channel conditions and any known high flow risks to public or private resources;
- available storage in Cachuma Reservoir (precautionary releases may not be appropriate when the lake is below elevation 745 or if no flow is entering the reservoir); and

- "watershed wetness" or antecedent index (modified operations may not be needed if the watershed is not wet).

5.2.2 Weather prediction and QPF

In order to determine the potential for high storm flows and reservoir spills, Flood Control will monitor weather prediction information available through its normal arrangements. As part of this evaluation, available QPF will be discussed with Reclamation and the basis of predictive modeling by Flood Control will be determined. Evaluation should consider the range of available QPF and other uncertainties of the available weather predictions. Either agency may initiate additional coordination regarding any revised forecasts available. Flood Control may rely solely on its experience in evaluating weather forecasts and in making any recommendation to Reclamation.

5.2.3 Initial modeling and recommendation

Flood Control will evaluate approaching storms to determine candidates for modified operations. Candidate storms will be further evaluated using the FCRIVER model and modeling results will be discussed with Reclamation. Based on modeling results and staff experience, Flood Control may recommend modified operations to Reclamation; every effort will be made to provide such recommendations in a timely manner. Reclamation decisions regarding modified operations should be made in a timely manner to allow Flood Control to implement appropriate storm specific measures in the downstream areas.

5.3 Monitoring and Data Accumulation

Flood Control will provide access to its ALERT System to Reclamation. Reclamation may monitor rainfall and other available data to meet its own data needs. Reclamation may independently verify data or evaluations made available by Flood Control. Flood Control will accumulate sufficient data upon which to base any recommendation for modified operations. Flood Control will inform Reclamation promptly if any such data are or may be unavailable for any significant period of time. Reclamation will make best efforts to supply reservoir condition and operations data to Flood Control before and at regular intervals during modified operations.

5.3.1 Rainfall and flow data

Data from six raingages are utilized to operate the FCRIVER model in "actual" (rather than "predictive") mode. These gage locations and backup stations are shown in Table 3. These gages are part of Flood Controls ALERT System and their data are telemetered to Flood Controls office in Santa Barbara. Backup data are available through telephone connections to other gages and by radio contact with Bradbury Dam and Gibraltar Dam personnel.

Data from five stream gages are utilized to monitor conditions during actual storm events; the five locations have corresponding model outputs as well. These gage locations and backup data are shown in Table 3. These gages are part of Flood Control's ALERT System and their data are telemetered to Flood Control's office in Santa Barbara. Backup data for flow immediately below Cachuma Reservoir and Gibraltar Reservoir are available through telephone connections or by radio contact with Bradbury Dam and Gibraltar Dam personnel.

Reservoir elevation and operations data are collected by operations personnel at Cachuma Reservoir and Gibraltar Reservoir respectively.

5.3.2 Reservoir condition and gate settings

Reclamation will provide lake elevation, previous hour inflow and gate opening (release rate) to Flood Control on an hourly basis during modified operations. In addition, any significant changes to gate settings will be communicated as soon as practical. Communications will be by telephone or radio.

5.4 Predictive Modeling

Flood Control will base predictive models on QPF and staff experience; several runs may be appropriate if a range of QPF are available. Reclamation may request additional model evaluation to test alternative modified operations scenarios. Reclamation may perform their own predictive modeling. Predictive modeling should be used to evaluate both flow in the River below Bradbury Dam and tributary flow.

5.5 Reservoir Operations

Reclamation is responsible for operational decisions for Cachuma Reservoir and operation of the spillway at Bradbury Dam. Reclamation may operate under the existing rule curve, under modified operations as described in this memorandum or may operate under some different set of parameters to protect public health and welfare. The modifications which Reclamation may consider include 1) "precautionary releases", 2) "prereleases", and 3) "gateholding" discussed in this memorandum. Operational decisions will be made by Reclamation operations supervisor, or designated representative, and implemented by operators of the reservoir. Any discussions regarding operational decisions should be between Flood Control's representative and Reclamation's operations supervisor and between the operations supervisor and the operators of the reservoir. Reclamation will implement specific operations for each inflow event, including potential modifications, after such discussions.

5.6 Watershed Conditions and Future Runoff

Flood Control will estimate future runoff based on existing watershed conditions and runoff measurements. Estimates of future runoff will be based on AI, historic records and anticipated upstream reservoir operations and will be provided to Reclamation, COMB and SYRWCD. Reclamation may prepare its own estimate of future runoff and rely on its own estimates in making operational decisions.

5.7 Report on Modified Operations

After any storm in which modified operations were employed, Flood Control will summarize actual storm conditions from its rainfall records and operations and flow conditions from Reclamation's operational records and USGS streamflow data. The summary will also include a summary of QPF predictions and modeling results so as to provide a basis for improved decisions on modified operations in the future. Such summary will be completed in a reasonable amount of time after modified operations, considering other ongoing operations by Flood Control and Reclamation and availability of flow data from USGS.

List of Figures

List of Tables

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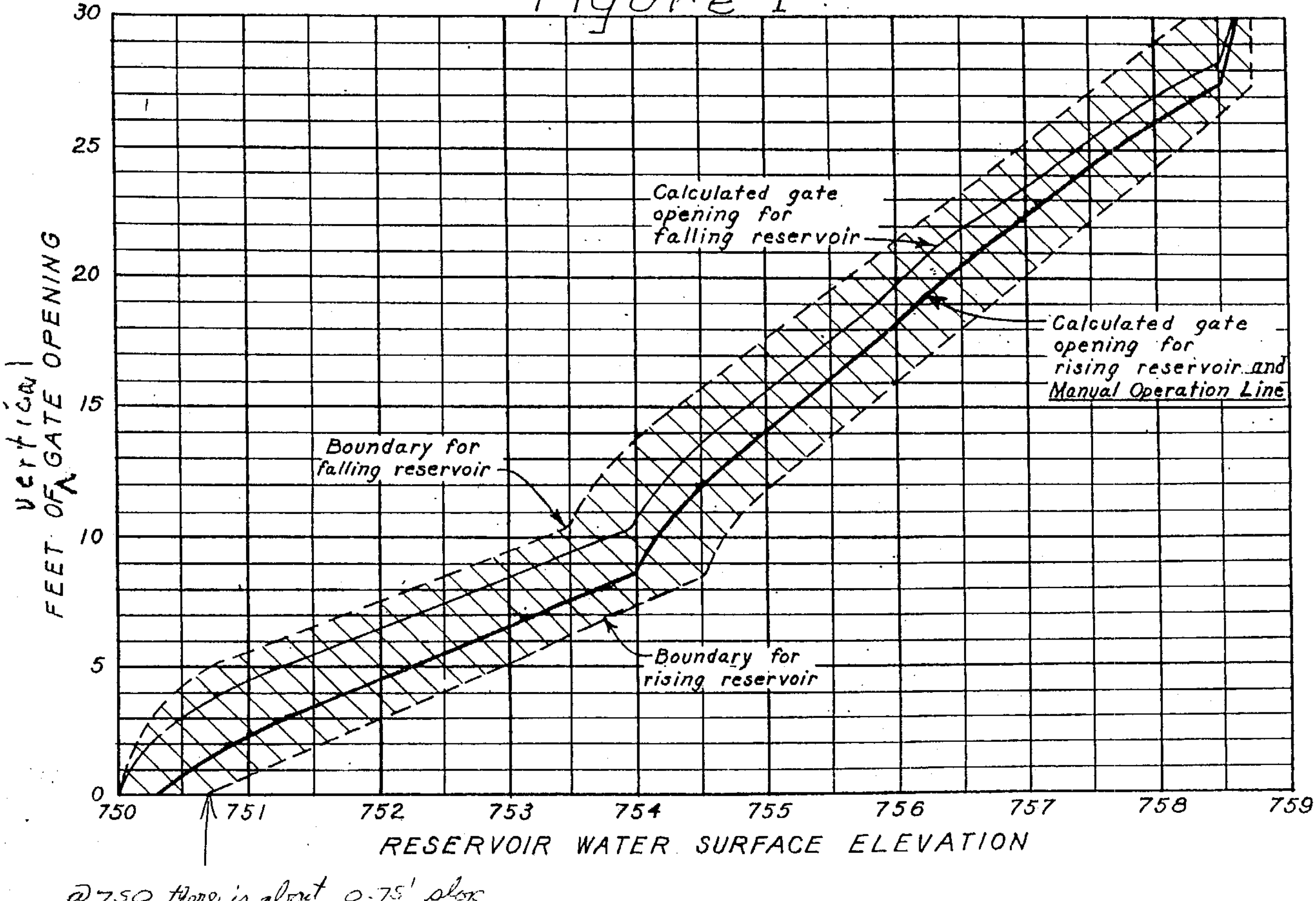
Figure 1



Bruce 9/11/93 GATE POSITION CHART

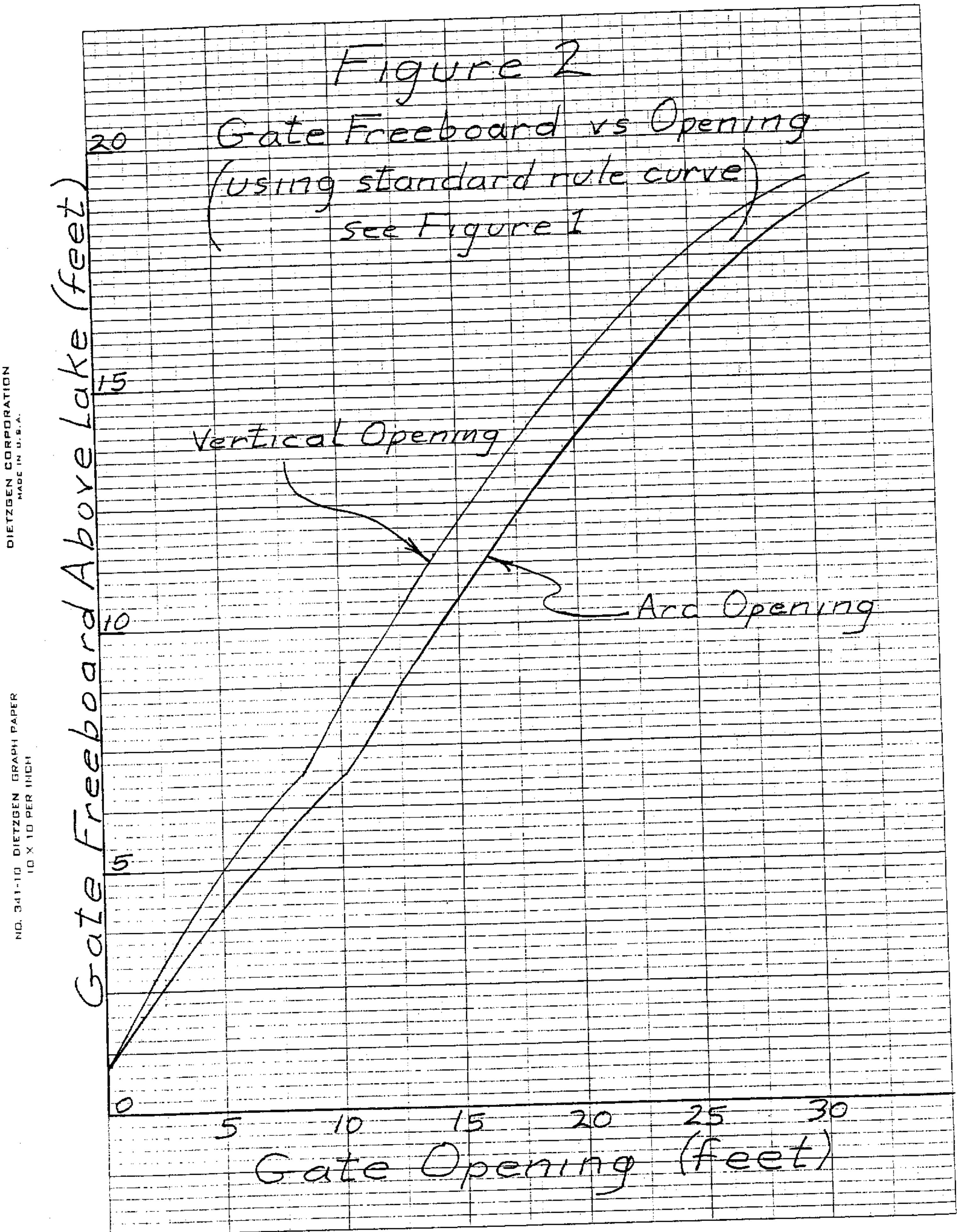
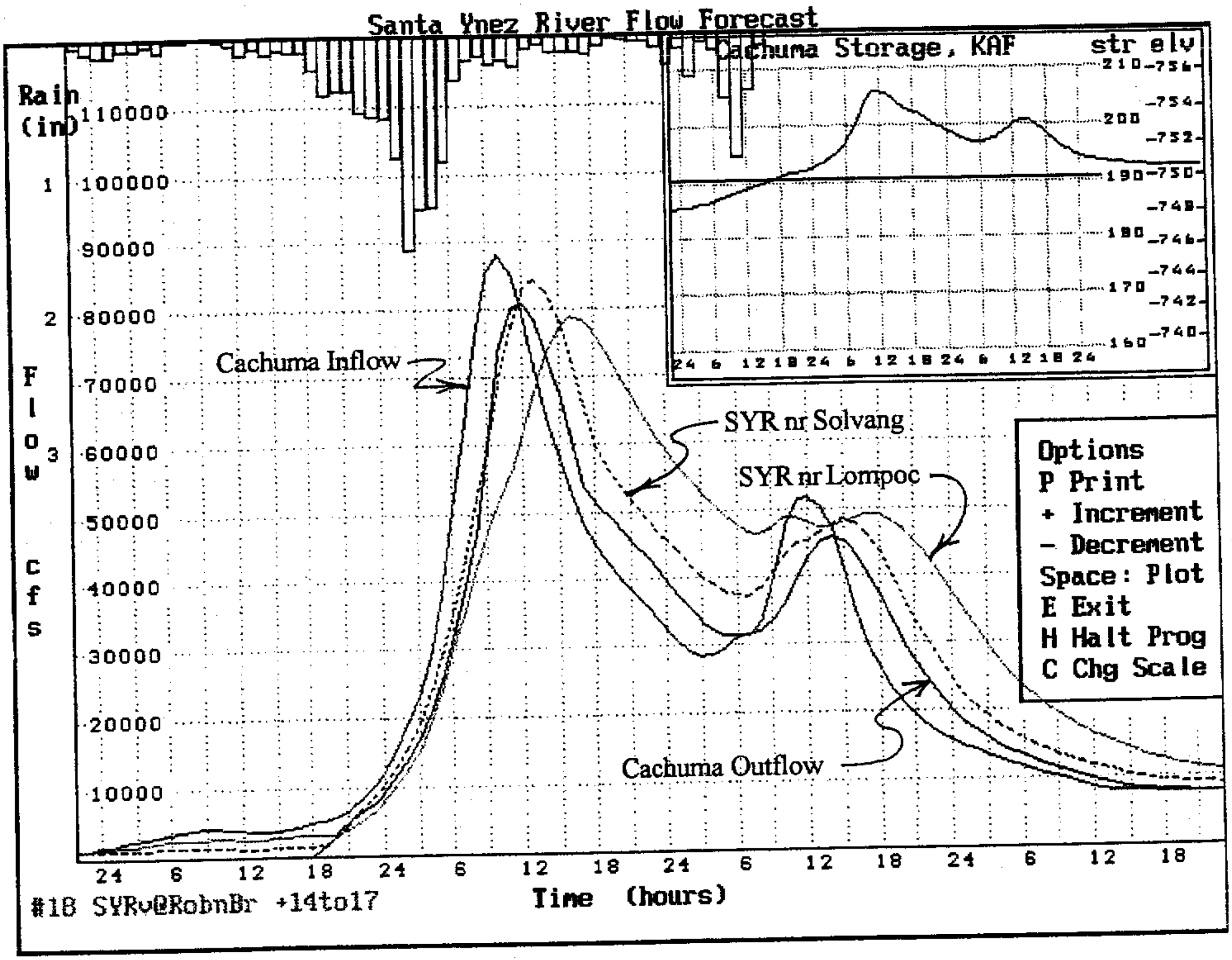


Figure 2
Gate Freeboard vs Opening
(using standard rule curve)
see Figure 1
Vertical Opening
Arc Opening
Gate Freeboard Above Lake (feet)
Gate Opening (feet)
0
5
10
15
20
25
30
DIETZGEN CORPORATION
MADE IN U.S.A.
NO. 341-10 DIETZGEN GRAPH PAPER
10 X 10 PER INCH

SBCWA: 6/26/98

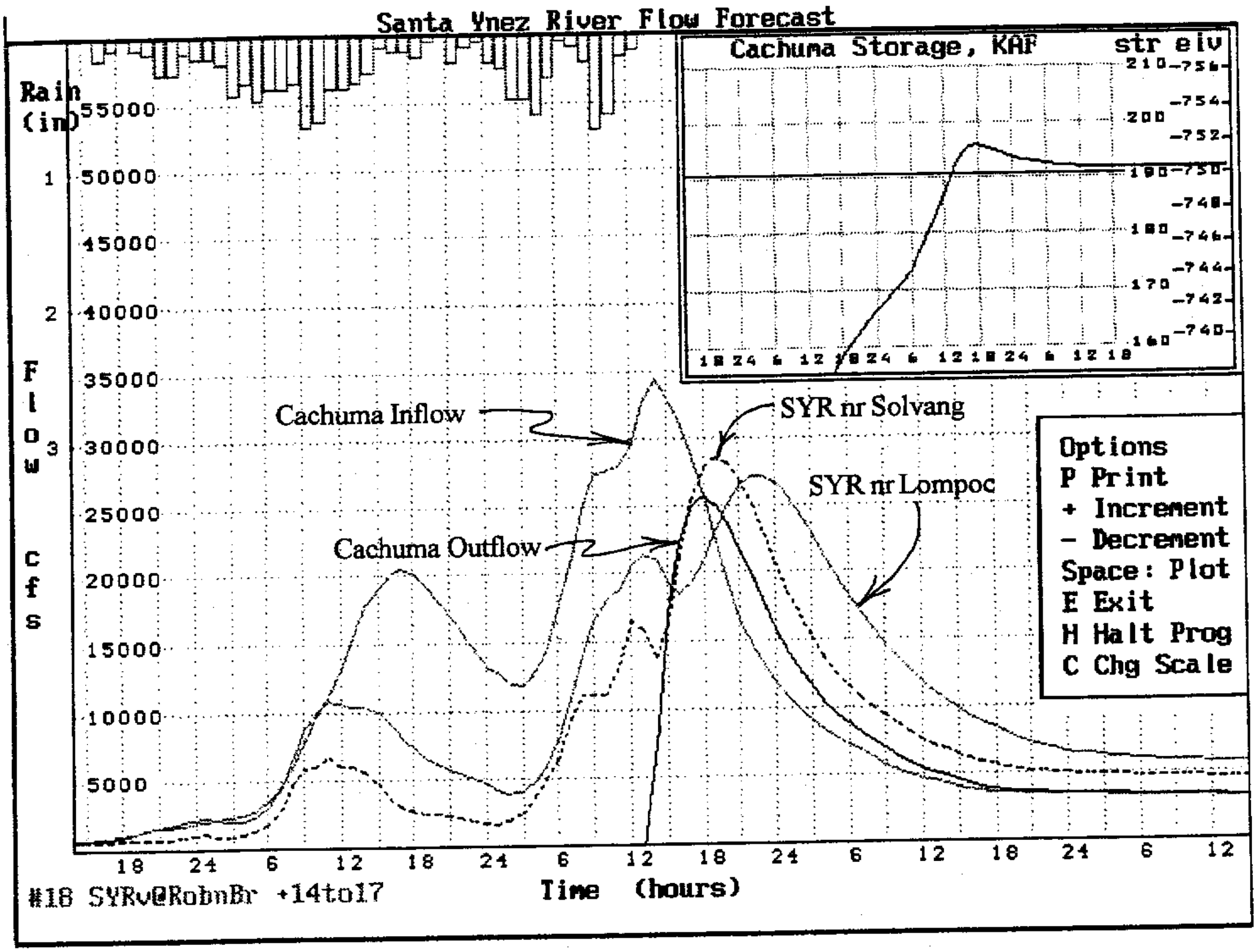
FIGURE 3



FCRIVER Modelling of the January 23rd - 26th, 1969 Storm Event

(Gibraltar Dam rainfall bar chart and Cachuma Storage graph at top of graph)

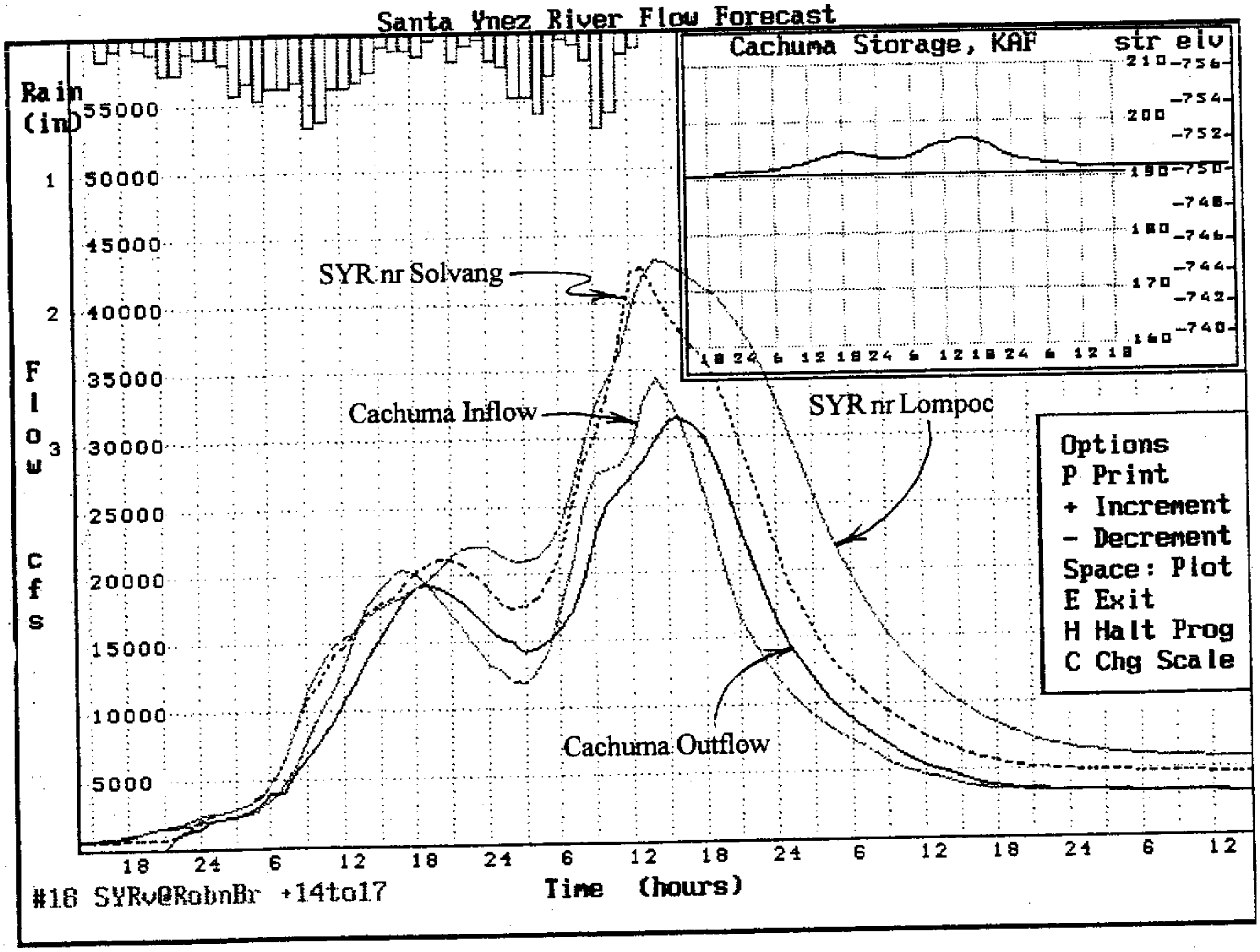
FIGURE 4a



FCRIVER Modelling of the February 1st - 3rd, 1998 Storm Event

(Gibraltar Dam rainfall bar chart and Cachuma Storage Graph at top of Graph)

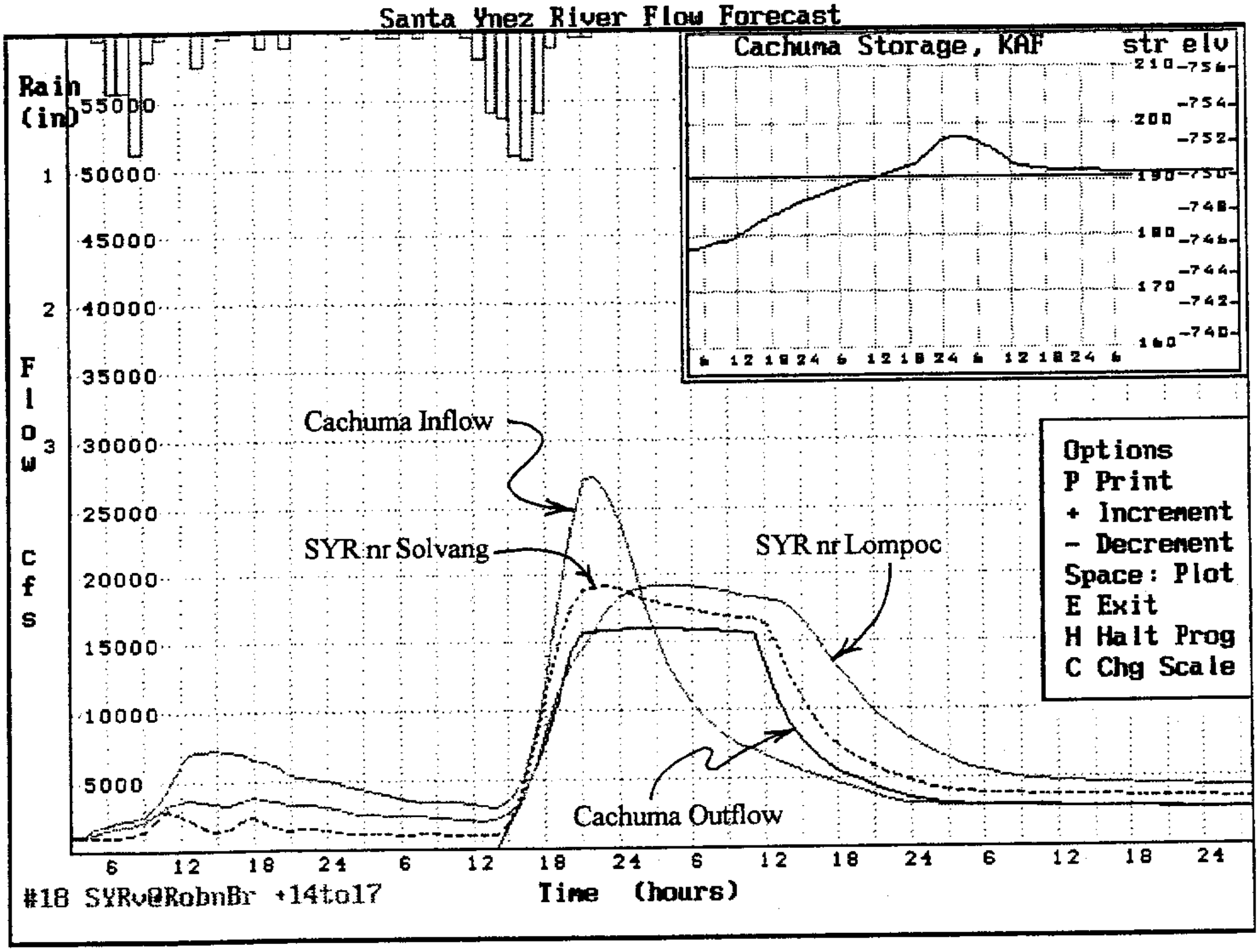
FIGURE 4b



FCRIVER Modelling of the February 1st - 3rd, 1998 Storm Event

(compare this graph to Figure 4; same storm, but reservoir start elev = 750 ft)

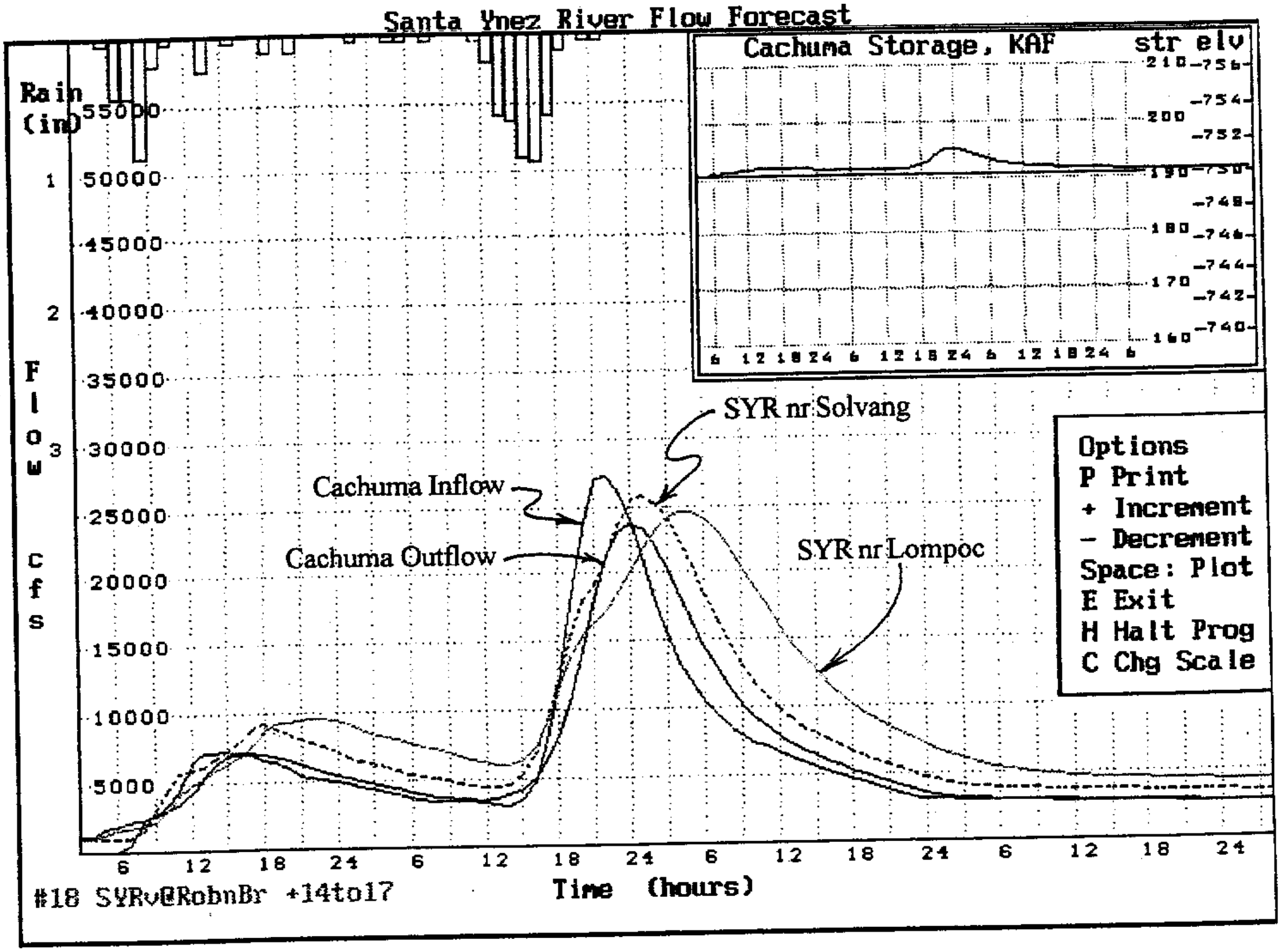
FIGURE 5a



FCRIVER Modelling of the February 6th - 8th, 1998 Storm Event

(this graph shows simulated historic hydrographs and reservoir performance)

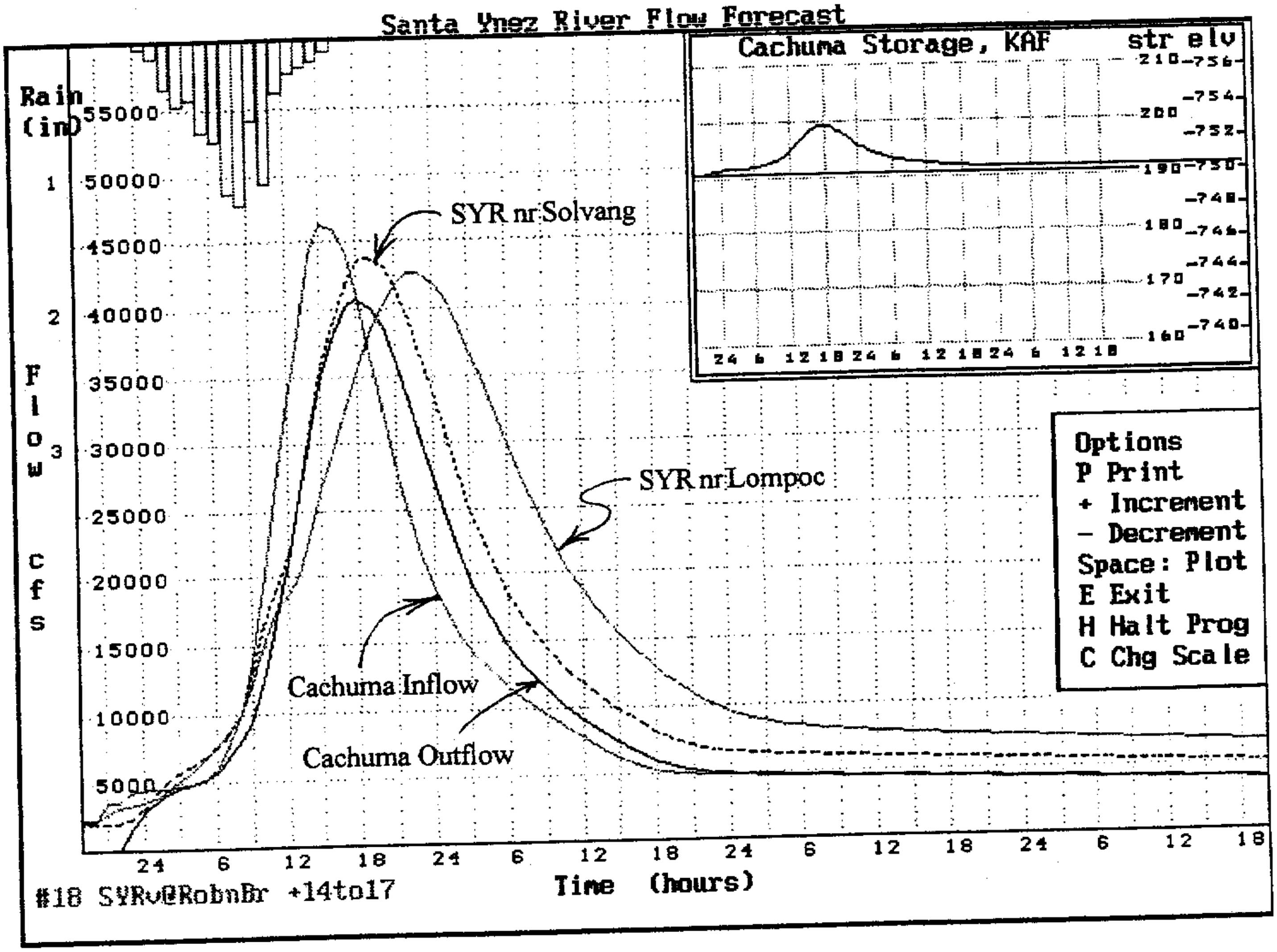
FIGURE 5b



FCRIVER Modelling of the February 6th - 8th, 1998 Storm Event

(graph shows standard operations without reservoir drawdown or gateholding)

FIGURE 6



FCRIVER Modelling of the February 23rd - 24th, 1998 Storm Event

(Gibraltar Dam rainfall bar chart and Cachuma Storage Graph at top of Graph)

SAI 'A BARBARA COUNTY FC' 'CD FLOOD WARNING NET 'ORK

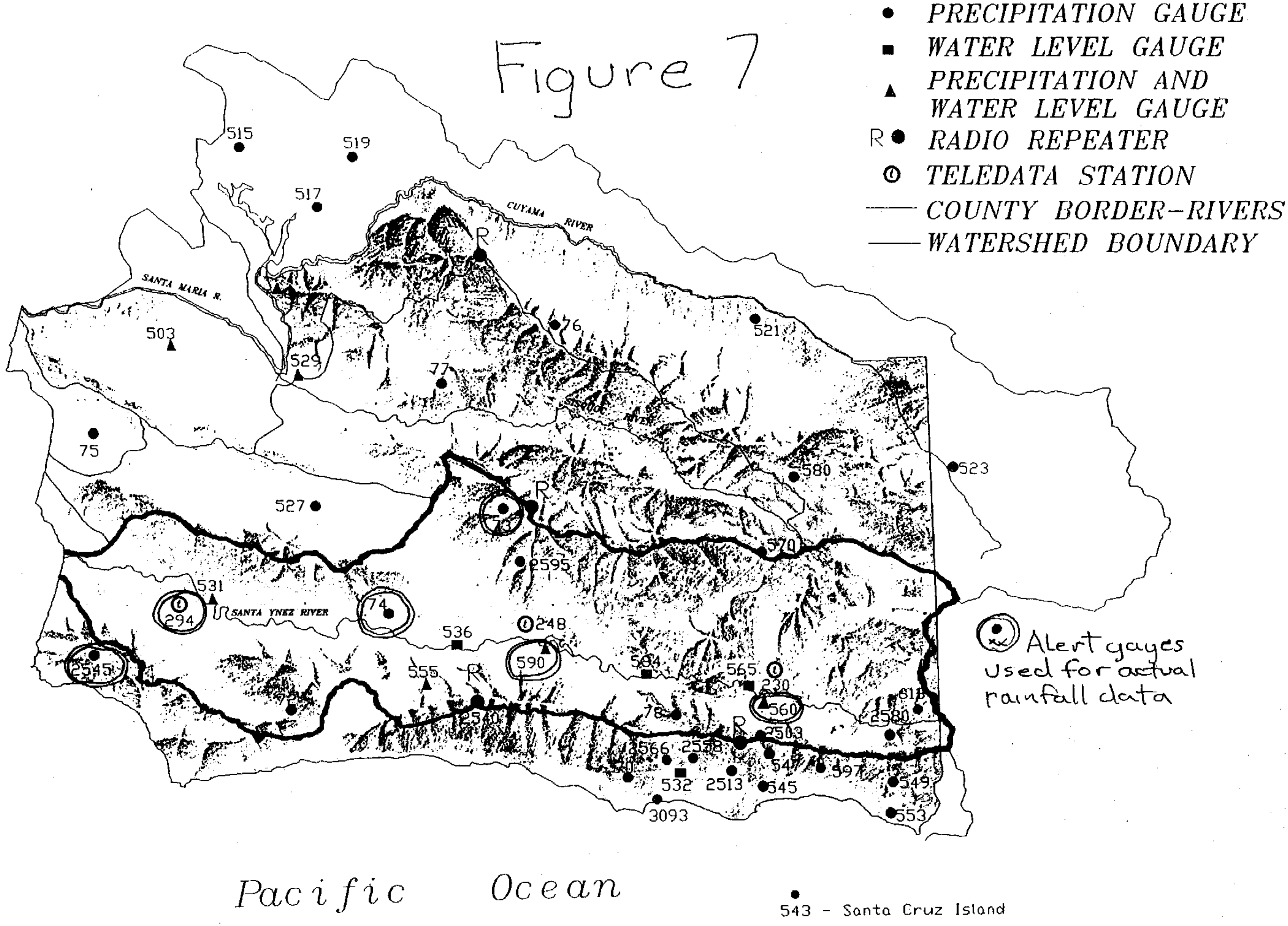


FIGURE 8

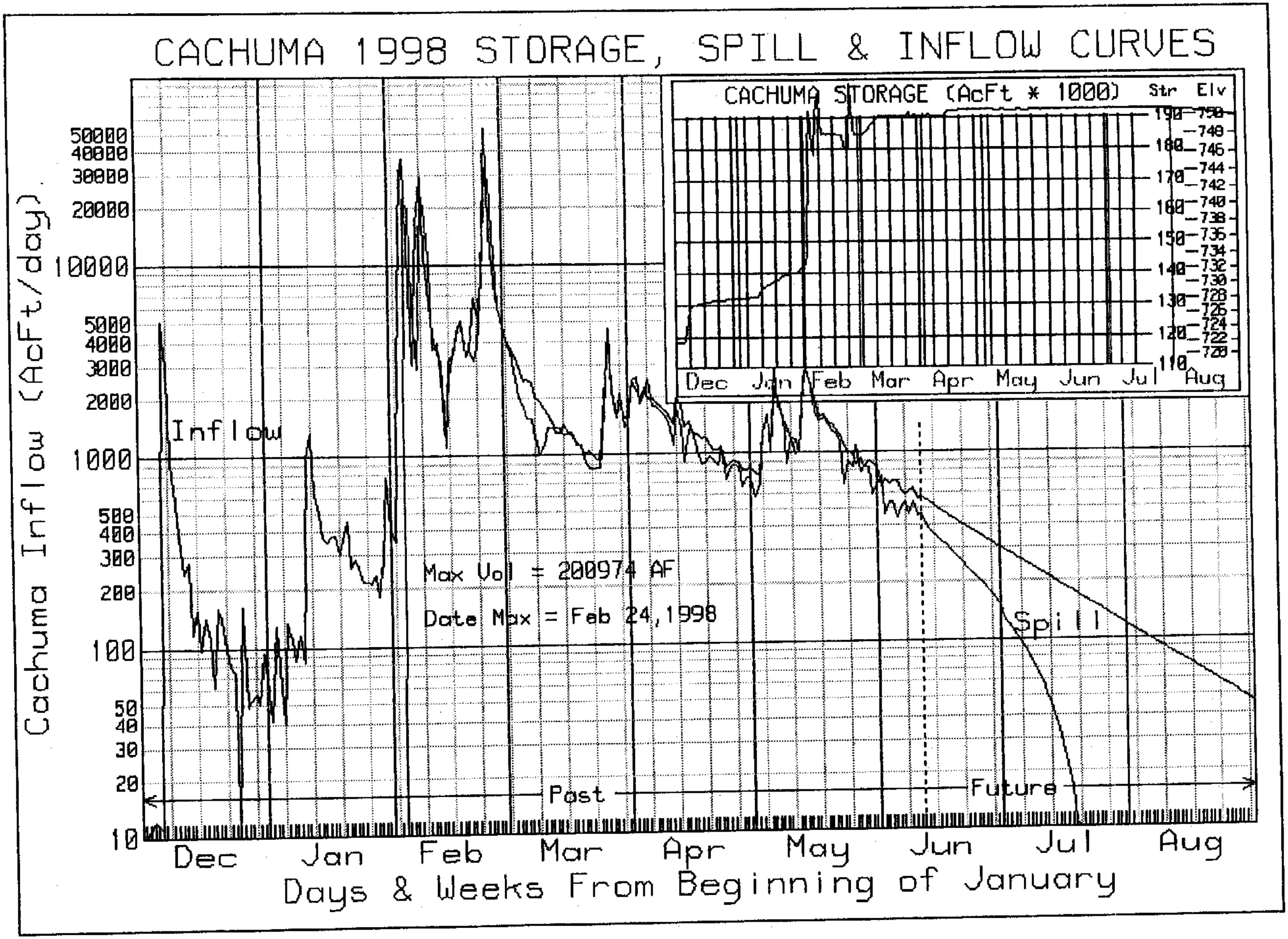
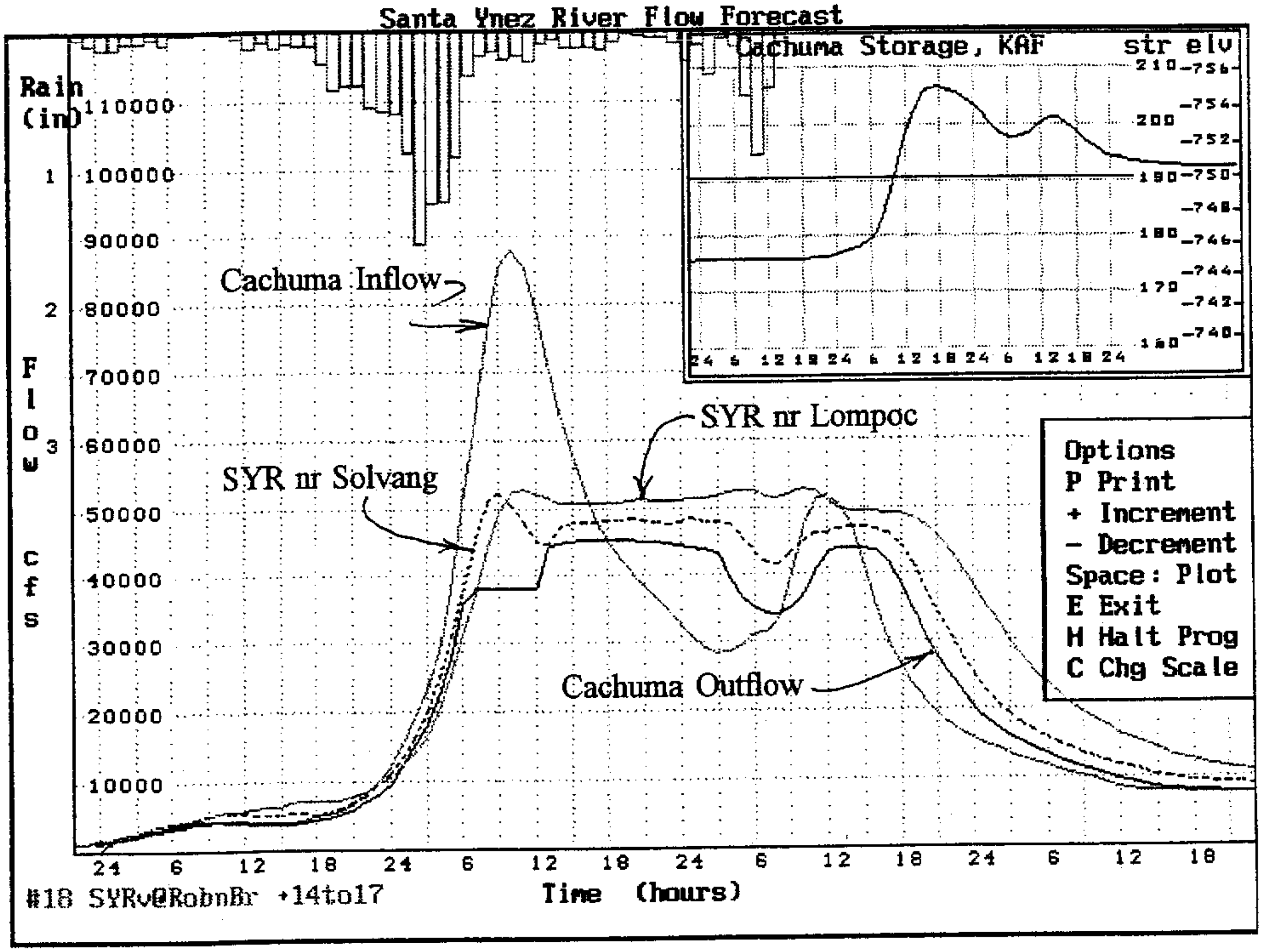

CACHUMA 1998 STORAGE, SPILL & INFLOW CURVES
CACHUMA STORAGE (AcFt * 1000)
Str Elv
190 750
740
180 746
744
170 742
740
160 738
736
150 734
732
140 730
728
130 726
724
120 722
720
110
Dec Jan Feb Mar Apr May Jun Jul Aug
Cachuma Inflow (AcFt/day)
50000
40000
30000
20000
10000
5000
4000
3000
2000
1000
500
400
300
200
100
50
40
30
20
10
Inflow
Max Vol = 200974 AF
Date Max = Feb 24,1998
Spill
Past
Future
Dec Jan Feb Mar Apr May Jun Jul Aug
Days & Weeks From Beginning of January

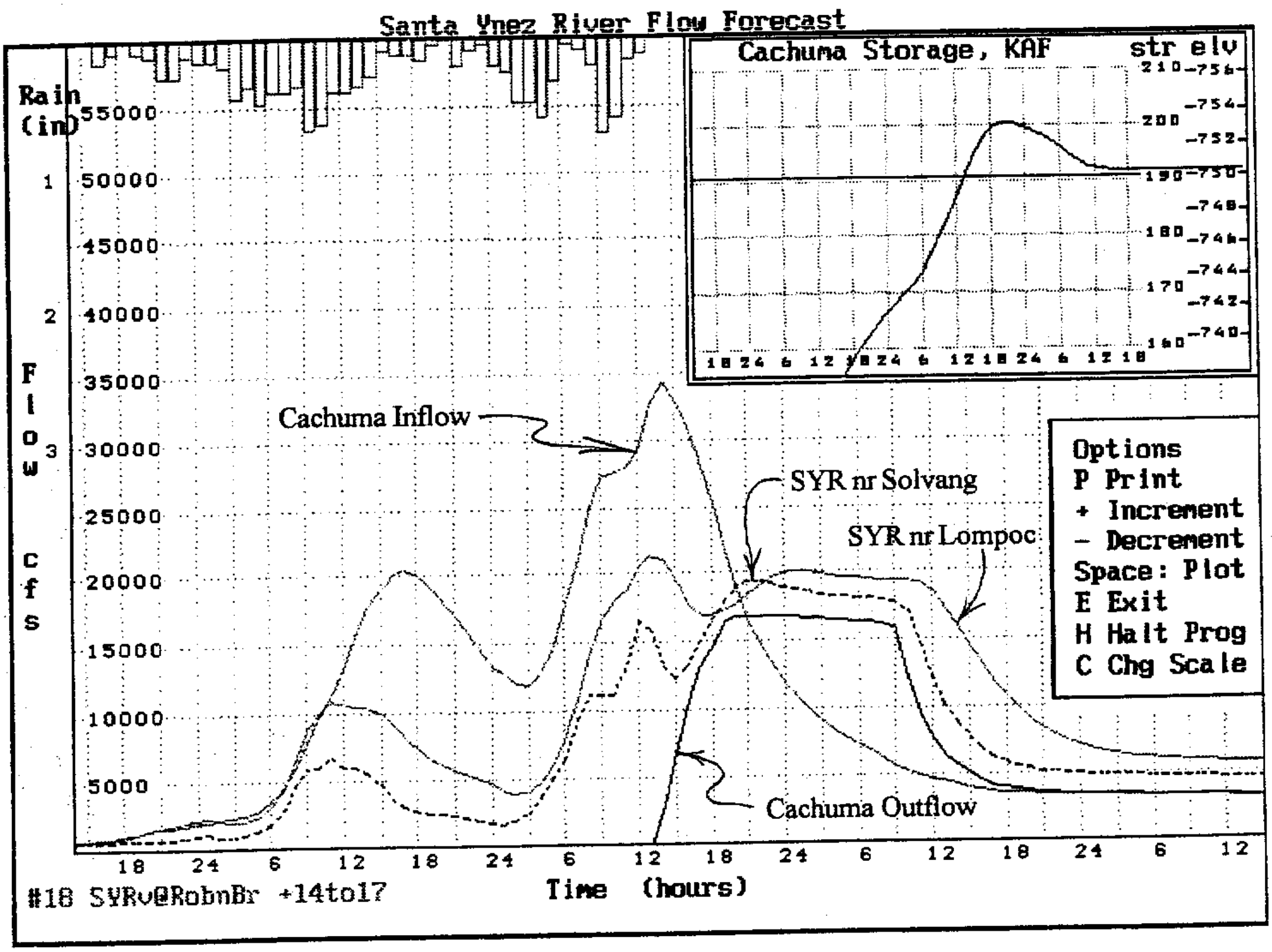
FIGURE 9



FCRIVER Modelling of the January 23rd - 26th, 1969 Storm Event

(see Figure 3 for standard operations; this Figure shows modified ops)

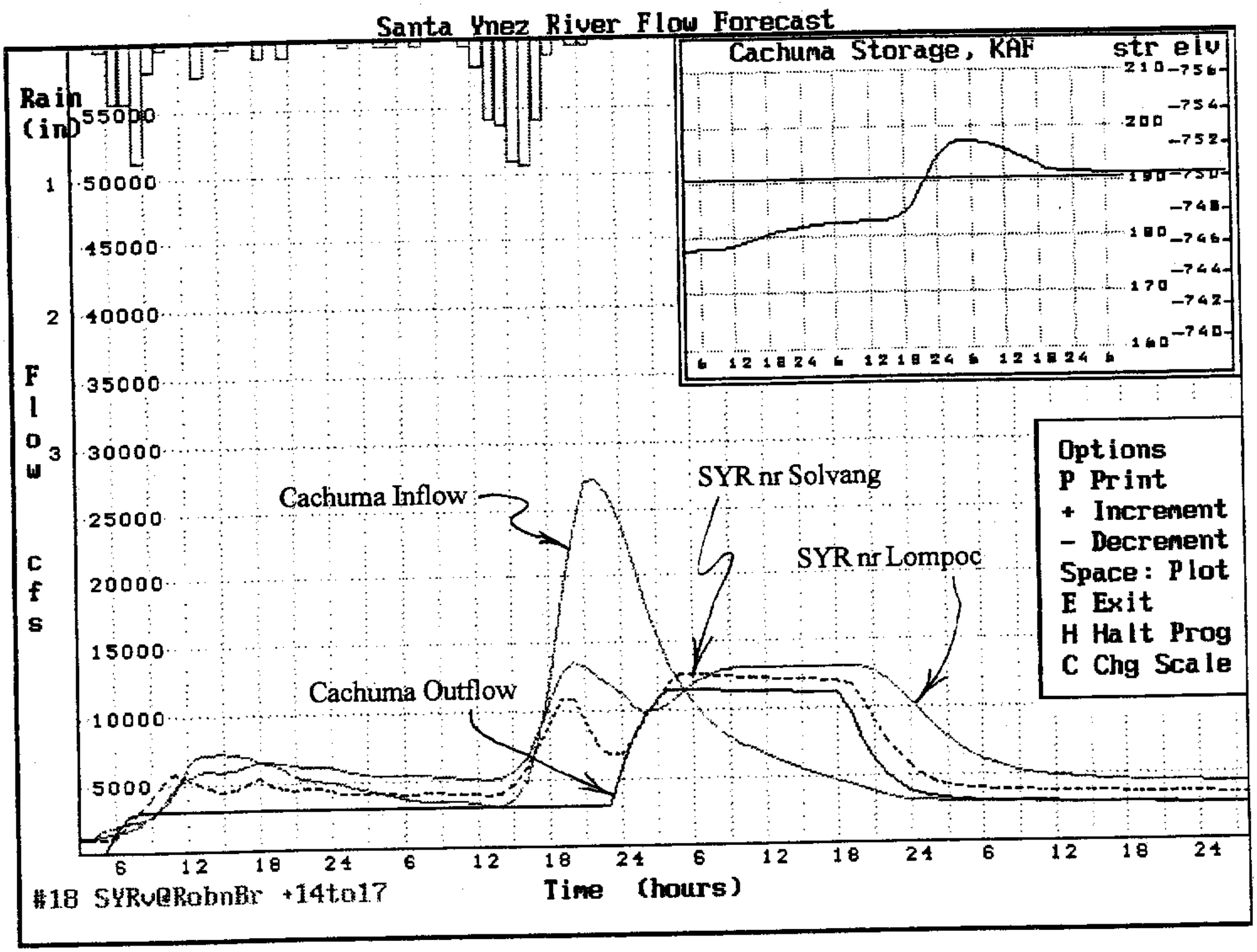
FIGURE 10



FCRIVER Modelling of the February 1st - 3rd, 1998 Storm Event

(see Figure 4 for standard operations; this Figure shows modified ops)

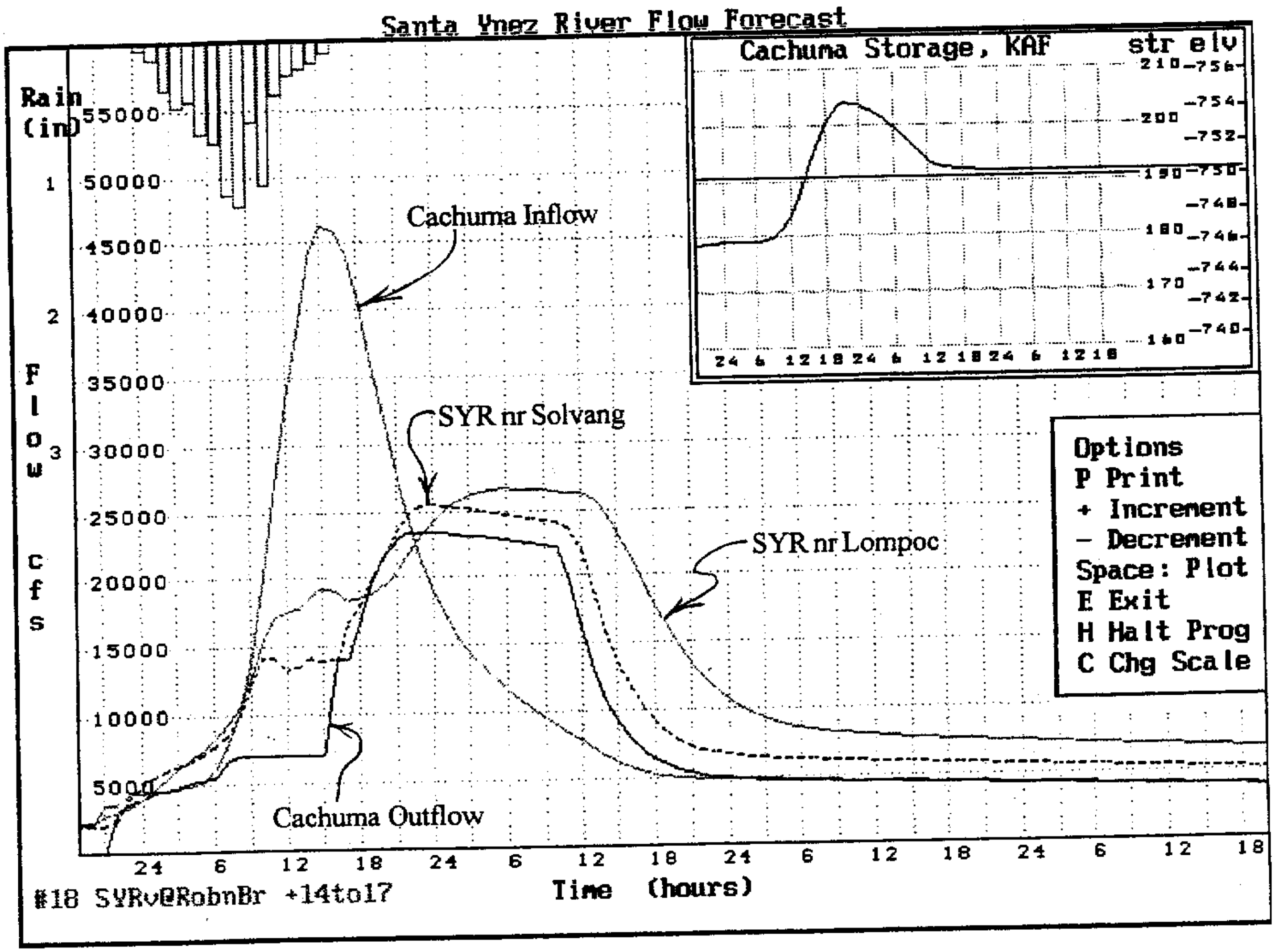
FIGURE 11



FCRIVER Modelling of the February 6th - 8th, 1998 Storm Event

(see Figure 5a &5b for comparison; this Figure shows all three modified ops)

FIGURE 12



FCRIVER Modelling of the February 23rd - 24th, 1998 Storm Event

(see Figure 6 for standard operations; this Figure shows modified ops)

Figure 13

Cachuma Winter Operations Interagency Contacts

Phase	Contact Responsibility
Pre-Storm Consultation	FCD → USBR
Initial Strategy Decision	USBR ↔ FCD; USBR ↓ Operations; FCD → EOC, COMB *, Lompoc *, SYRWCD *
During Event	USBR ↔ FCD; USBR ↓ Operations; FCD → {with significant changes only} → EOC, COMB *, Lompoc *, SYRWCD *
Report on Modified Operations	USBR ↔ FCD; USBR ↓ Operations; FCD → COMB, Lompoc, SYRWCD

* Contact by phone or fax, time permitting

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TABLE 1

Significant flow events at Solvang and
Los Laureles Gages,
Santa Ynez River
(Storms Which Produced flows Exceeding 20,000 cfs)

YEAR	DATE	LOS LAURELES (above Cachuma)	SOLVANG (Below Cachuma)
1966	December 6	x	
1969	January 21	x	
1969	January 25-26	x	x
1969	February 24-25	x	x
1978	February 10	x	
1978	March 4	x	x
1983	March 1-2	x	x
1992	February 12	x	
1995	January 10	x	x
1995	January 24-25	x	
1995	March 11	x	
1998	February 1-2	x	x
1998	February 6-7	x	
1998	February 23-24	x	x

TABLE 2

Comparison of Modified Cachuma Operations for the February 23rd - 24th Storm

(all numeric results are from runs using FCRIVER flood flow forecasting program version FCRPRGH.BAS)

Run Conditions	Cachuma Peak Flows (cfs) Inflow	Outflow	% Reduction in Cach Qout	S.Y.River @ Solvang (cfs)	% Reduction in Solvang Q	S.Y.River @ Narrows (cfs)	% Reduction in Narrows Q
No Action*	46,389	40,791		43,810		42,625	
Pre storm 4 ft drawdown only	46,389	39,141	4.05%	41,696	4.83%	39,280	7.85%
7000 cfs early release only	46,389	40,717	0.18%	43,714	0.22%	42,385	0.56%
Gatehold starting @ 2.5 ft only	46,389	30,131	26.13%	32,542	25.72%	33,577	21.23%
4 ft drawdown + 2.5 ft gatehold	46,389	27,325	33.01%	29,603	32.43%	30,549	28.33%
4 ft drawdown + 7K pre-release	46,389	35,235	13.62%	37,145	15.21%	34,875	18.18%
Sum of individual mods %			30.36%		30.76%		29.64%
Combination of all three mods	46,389	23,397	42.64%	25,464	41.88%	26,606	37.58%

* The "No Action" run models Cachuma operations without any of the three operational modifications Summarized above. Start of storm lake elevation is 750 ft, MSL, and the spillway gate openings are determined based upon lake elevations following the standard rule curve (Figure 1).

The "synergy" of combining modified operations is evident by comparing the percentages in flow reduction due to one modified operation at a time, with the percentage reductions of the various combined operations presented in this table...

SBCWA: CMODST2.XLS; 7/02/98

TABLE 3

STORM OPERATIONS MODEL, DATA SOURCES AND BACKUPS

RAIN GAGES

LOCATION	BACKUP
Gibraltar	RUGID 8 (dial in) or Damtender observation of gage
Cachuma	Damtender observations of gage
Figuroa Mountain	LARK (dial in)
Buellton	Backup not critical to modeling, data may be estimated
Lompoc (City)	Robinson Bridge (Alert)
Sudden Peak	Backup not critical to modeling, data may be estimated

STREAM GAGES

LOCATION	BACKUP
SYR Below Gibralter Dam	Damtender report of gate settings
SYR @ Los Laureles	Backup not critical, data may be estimated
SYR below Cachuma	Damtender report of gate setting
SYR @ Solvang	Backup not critical, data may be estimated
SYR @ Lompoc (246 bridge)	Backup not critical, data may be estimated

RESERVOIR LEVELS

LOCATION	BACKUP
Gibraltar	RUGID 8 (dial in)
Cachuma	BDT (dial in)

GLOSSARY OF TERMS

Early Storm Inflow Release- release at a rate greater than the rule curve in anticipation of inflow from measured rainfall; these releases are intended to maintain reservoir elevation lower than that which would occur pursuant to the rule curve. (This operation may occur when lake elevation is below elevation 750.)

Estimated Peak Inflow - Peak rate of storm runoff into the reservoir calculated by FC RIVER model based on QPF or measured rainfall.

Gate Hold - An operation which allows the reservoir elevation to rise towards the top of the gate without raising the gate the amount stipulated by the original rule curve to maximize surcharge, and minimize maximum rate of releases. This may be holding the gate opening constant or raising the gate in small increments to keep the reservoir elevation just below the top of the gate.

Gate Opening (arc) - The measurement of gate opening along the radial arc described by the bottom of the gate.

Gate Opening (vertical) - The difference in elevation between the spillway invert and the bottom of the gates.

Modified Operations - Reservoir operations which differ from the original rule curve and which are intended to reduce the peak storm related releases using pre-releases, and gate hold techniques.

Precautionary Release - Deliberate release greater than inflow intended to lower the lake elevation below elevation 750 in anticipation of a significant storm inflow event.

Pre-release - Release of water from the dam in advance of a storm which is in excess of releases stipulated in the original reservoir rule curve.

QPF (Quantitative Precipitation Forecast) - Estimates of rainfall amount expected for a specified period of time in a particular area

Release - Outflow of water from the reservoir through the spillway, siphon or release works pipeline control valves.

Remaining Watershed Runoff (Expected Inflow) - The volume of remaining seasonal inflow in the absence of any future rainfall.

Rule Curve - Original reservoir operational parameters (Figure 2 "Gate Position Chart", USBR).

Spill - Releases when the lake is above elevation 750, and when inflow is greater than diversions and evaporation.

Stormwater Release - Releases during a storm event

Surcharge - A reservoir condition when the water surface is above the original definition of "full" or normal operating level with no spill.. Cachuma Reservoir surcharge occurs when the lake elevation exceeds 750.0 ft. MSL.

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APPENDIX A

EXAMPLE STORM CONDITIONS

FCRIVER MODEL DATA

January 23-26, 1969

From September, 1968 to January 14th, 1969 the seasonal total rainfall at Gibraltar Dam (considered the key precipitation site for the watershed above Bradbury Dam) was just 5.54 inches, still classified as a somewhat dry condition for the watershed. Then, starting January 18th, up to the early part of January 23rd, a strong winter storm brought 15.1 inches of rainfall at Gibraltar Dam and 22.5 inches at Juncal Dam at the south-east end of the Santa Ynez River watershed. Almost all of that precipitation had fallen by the morning of January 22nd. The watershed condition became quite wet with this large storm. Following this, a persistent light rainfall began falling late at night on January 23rd, and contined to 1800 hours on January 24th. The rainfall then intensified overnight, and through the early morning of January 25th, with the highest intensities occurring between 7:00 PM on the 24th and 7:00 AM on the 25th, dropping 8.75 inches at the Gibraltar and 13.12 inches at the Juncal guages during this 12 hour period. Between 2:00 AM and 5:00 AM on the 25th Gibraltar recieved 4.04, and Juncal recieved 4.43 inches. The total (60 hour) rainfall from late night on the 23rd to 10:00 AM on the 26th was 15.1 inches (again!) at the Gibraltar, and 23.0 inches at the Juncal guages. By late morning on January 25th, the Cachuma inflow rose to an hourly peak value of 89,000 cfs. The Cachuma outflow peaked at 80,000 cfs around noon, and the flows entering Lompoc Valley peaked around 4 to 5:00 PM in the afternoon at about 80,000 cfs. Light rain continued falling through January 25th with a smaller system passing the County during the morning hours of the 26th. This system brought a secondary peak of approximately 50,000 cfs into Cachuma reservoir by about noon on the 26th, and kept flows entering Lompoc valley between 45,000 and 50,000 cfs until late night of the 26th, after which the flows recessed as only sporadic amounts of light rain fell on the watershed over the next three days. The damage wreaked by this storm above and below Cachuma, and especially in Lompoc Valley was extensive and devastating. At the time (1969) the flood was thought to be a 50 year event, but subsequent USBR studies (1994) suggest that the flows were the largest in the river between Cachuma and Lompoc in 2,900 years.

An effort has been made to simulate this storm using the FCRIVER model. A graphical display of the storm is shown on Figure 3. The Figure should be a faily good approximation of what actually occured in terms of flow magnitudes, Cachuma storage and etc.. Using the model with the same storm data base (i.e. 60 hours of rainfall data for six guages), but starting flood operations with the lake drawn down five feet below the 750 ft, MSL full level, releasing early storm inflows (previous hours inflow, of course, is meant) up to 38,000 cfs, and gateholding, beginning at the opening corresponding to the max early release level, results in a 33% reduction of the maximum flows experienced in Lompoc Valley compared to the flows which occured under normal operations (see Figure 9).