Development of a Folsom Reservoir Release Rule Using Flow Forecasts

By

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Contents

Table of Figures

Table of Tables

1. Abstract

This study determines the flood risk reduction benefits and water supply tradeoffs of reservoir release rules which incorporate 1- to 3-day forecasts of volume and flow, and which limit releases based on forecast uncertainty. A forecast-based release rule for Folsom Reservoir on the American River is developed in a reservoir simulation model, compared with rules proposed by others, and evaluated for 6 200-year hydrographs with 2 initial storages. For each shape and initial condition, 5 artificial forecasts and a perfect forecast are simulated to evaluate sensitivity to different types of forecast errors, and simulations for 1-, 2-, and 3-day lead times are compared.

Based on user-specified thresholds, the rule evaluates whether forecasted inflows or storage threaten the reservoir and prescribes advance releases up to channel capacity to provide needed additional flood storage space. Forecast uncertainty is estimated using historic information, and the advance release is constrained to a user-specified probability of refill based on this estimated uncertainty. The flood risk for each operational change is assessed using estimated levee fragility curves, simulated flow durations, and hydrograph weightings. The water supply impacts are determined by the probability of refill.

Lower refill probabilities increase water supply impacts and decrease flood risk. Shorter lead times increase storage in the reservoir and decrease advance release. Early and low artificial forecasts challenge operations more than late or high forecasts, but still reduce the probability of failure. Incorporating short-term forecasts with uncertainty into Folsom's operations reduces magnitude and duration of peak outflows for the 200-year flood. When forecast uncertainty is better quantified, refill probability can be varied to optimize for flood control and water supply.

2. Introduction

Rule curves are used to operate reservoirs for flood management. These rule curves, which specify a target reservoir elevation and flood pool size for each time of year, reflect a tradeoff between conflicting objectives of water supply and flood protection. A smaller empty flood pool allows more of the reservoir to be used for water supply and recreation, but maintaining a larger empty flood pool allows better peak attenuation during floods. The flood pool size is usually set in advance of the flood season, based on the peak flows in the period of record. Traditionally, flood operations begin when reservoir elevation rises above the target elevation, and the stored water encroaches into the flood pool. During a flood, reservoir operators decide in real time whether to store or release water. Operations can thus be divided into two types: operations which increase preparedness for a potential flood, and operations which react to a current flood event.

Flood protection can be increased by incorporating short-term forecasts into the flood operations to initiate releases earlier, even before the reservoir is encroached. By increasing the period of time over which the operators can make releases, lower and steadier releases can be made. Forecast-based operation could thus better link preparatory actions and emergency operations.

Although operation with forecasts is not within the current USACE policy, several studies of Folsom Reservoir indicate that the reservoir is an excellent candidate for forecast-based operation (Yao and Georgakakos 2001, USACE 2002, Bowles et al. 2004, MBK Engineers 2012). A lower spillway (under construction) will enable operators to release more water at a lower reservoir elevation. The current re-operation study for the lower spillway provides an opportunity to assess possible benefits of operation with forecasts. This thesis focuses on creating forecast-based operating rules which are practical and can feasibly be implemented by reservoir operators.

The following sections provide a background of Folsom reservoir and the American River watershed, and reviews of the recent literature on forecast-based operations. Error analysis is conducted on the available historical forecast data, and a method for developing synthetic forecasts is presented. Synthetic forecasts are created for 6 different event shapes scaled to an estimated 200-year recurrence; to capture a broad range of possible outcomes, sets of forecasts are generated for cases in which forecasts are early, late, overestimates or underestimates of the peak. A perfect forecast is also used for each event.

The historical and synthetic forecasts are then implemented in an existing reservoir simulation model (HEC ResSim) to evaluate operating rules. Different rule start triggers, forecast lead-times, and refill probabilities are evaluated. Promising operating rules are compared against proposed rules from other groups and agencies to evaluate flood control and water supply performance. Flood control performance for each rule is analyzed by applying the simulated timing and duration of flows for several synthetic events to geotechnical fragility curves, then determining the probability of levee failure. Water supply performance is determined by the probability of refill and the likelihood of ending the month encroached for the period of record. Methods for finding an optimal balance between water supply and flood control are discussed. Finally, conclusions are made about the potential benefits of forecast-based operations for Folsom Reservoir.

3. Background

3.1. Project Background

Folsom Dam was constructed in the 1950's by the U.S. Army Corps of Engineers (USACE) and has been operated by the U.S. Bureau of Reclamation (USBOR) as a part of the Central Valley Project since its completion in 1956. The dam was constructed to provide an estimated level of flood protection of 1 in 1,000 years with a maximum release of 115,000 cfs (USACE 1950). Since the construction of the dam, however, record-breaking floods such as the floods of 1956, 1965, 1986 and 1997 have changed the estimates of flood frequency to 1 year in 85 (USACE 2001).

The Joint Federal Project between USBOR and USACE is an effort to improve Folsom Dam's flood protection and address the dam safety risk. Among other components, the two agencies are constructing an auxiliary spillway to enable releases at lower elevations. A reoperation study is underway to specify operations of the dam with the new additions; the objectives are to maintain flows below 160,000 cfs in the American River below Folsom Dam while passing a 1-in-200 year flood event, and to pass the probable maximum flood (PMF) with a minimum of three feet of freeboard on Folsom Dam. One operational change under consideration is the use of forecast-based operations.

Since the reservoir operation manual was updated in 1986, forecast technology has improved. Atmospheric rivers such as the event which occurred in 1997 can now be predicted several days in advance. The National Weather Service (NWS) California/Nevada River Forecast Center (CNRFC) provides American River streamflow forecasts using two systems- the operational forecast system (OFS) and the ensemble streamflow prediction (ESP) system. OFS incorporates real time observed and projected information as well as historical analysis to create a new 5 day forecast every 6 hours. ESP uses the same information, but instead uses the historical information to create forecast traces for each year of historical calibration data. The traces generated by ESP can extend up to one year in the future, although such long forecast traces are ineffective for flood forecasting.

The current policy of the USACE is to base operations only on the water which has already fallen in the watershed; future inflow is derived from hydrologic models that route gauged upstream flow and precipitation. This method provides 4 to 12 hours of lead time (USACE 2002). As such, forecast information is currently not explicitly implemented in any of the reservoir models, although it is used to inform decisions made by reservoir operators. The USACE Sacramento District receives and uses the CNRFC's 5-day, 6-hour operational forecasts. The 1987 Water control manual states that to minimize surcharge and assure the safety of the dam the operator may "on the basis of forecasts, make releases somewhat greater than those required by the [emergency release] diagram" (USACE, 1987). A method of systematically using forecast information to make operating decisions was not proposed in the 1987 manual, however.

One method of incorporating forecast-based operations into the existing Folsom simulation model would be to adjust the top of the conservation pool (TOC) upward or downward based on forecast information. Another method would be to create a standalone rule to process the available information and make a release decision. This study will focus on a standalone rule since it would provide more flexibility in the event of communication blackout; others are investigating the possibility of guide curve adjustment for the reoperation study.

3.2. Literature Review

In addition to the ongoing reoperation study, several significant studies have been completed on forecast operations and Folsom's guide curves.

Georgakakos et al. have attempted to optimize rules for hydropower generation which achieve a minimum level of refill and minimize energy spill and flood damage. Yao and Georgakakos (2001) emphasized the importance of characterizing the forecast uncertainty, since the bias, reliability, and spread of the forecast model determine the value of the forecasting scheme. Biased forecasts could lead to under- or over-estimating future reservoir levels, and widely-spread forecasts could lead to less use of the flood pool's flood regulating capacity. Unreliable forecasts could lead to releases above channel capacity, releases below environmental requirements, reduced storage for water supply, or increased storage of water at elevations which threaten the spillway. Yao and Georgakakos found that reliability is the most important factor for large reservoirs, and bias and spread are key for maximizing use of small to mid-size reservoirs. Although the study routes perfect forecasts only, and thus represents an upper bound to the possibilities of forecast-based operation, Yao and Georgakakos found that operations which quantify and incorporate forecast uncertainty are superior to operations which assume forecasts are perfect.

For the forecasting models to improve operations, the information must be used effectively and dynamically. Yao and Georgakakos (2001) found that forecasts used with traditional rule curves provided little change in expected flood damages or hydropower generation. Forecasts used with dynamic rules are able to increase releases before high flows and increase water storage as the peak passes, improving hydropower generation, avoiding flood damages, and maintaining minimum environmental flows.

A possible dynamic use of information would be to use guide curves with changing indices rather than traditional static curves. In the past, the operations for Folsom included changing guide curves based on indices of basin wetness, which informs flooding potential. The rate of refill varied by up to 80 TAF per month between February 15 and April 20, depending on a precipitation parameter which adds the current day's precipitation in inches to a set percentage of the previous day's parameter (USACE, 1986). In addition, Maher (2011) proposed and evaluated several variable-index guide curves based on precipitation, snowpack, and climatic indices. Guide curves were assessed based on water refill probabilities and flood performance. Maher concluded that information about local watershed conditions could be effectively incorporated into the rule curve, provided a method for incorporating them daily, and presented performance tradeoffs between flood control and water supply. Larger flood pools operated best for balancing the performance of water supply and flood control.

USACE operation of Folsom is currently static with respect to watershed conditions, however. Guide curves are currently adjusted upward or downward based only on empty storage volume available upstream (USACE 2004). Long-term forecasts or ensembles could be used alongside other parameters such as basin wetness, snow-pack, and upstream storage space to determine the overall level of flood risk in the basin and adjust the guide curve accordingly. If no large streamflows are forecasted, the flood pool could be smaller and the top of the conservation pool could be adjusted upward; if a large streamflow is forecasted, the flood pool should be larger and the top of the conservation pool should be adjusted downward. This topic is currently being studied by a multi-agency technical group.

Another possible dynamic use of information would be to incorporate short-term forecasts into the operating rules. Short-term forecasts of 5 days or less can be used to prescribe a minimum or specified release in advance of a flood. A USACE study by the Hydrologic Engineering Center (HEC) discussed this concept in detail (USACE, 2002). The study proposed, described, and simulated rules for "Advance Release"—a release that makes additional storage volume available in response to NWS streamflow forecasts. The proposed rules allowed conservation pool drafting and ranged in complexity from a simple increment-based release with less dependence on forecasts, to a more forecast-dependent volume-based release which attempts to maintain 99% refill probability. The study also investigated the benefits and risks of advance release for flood control, water supply, and hydropower generation. USACE found that drawdown decreased and the probability of exceeding 115,000 cfs increased as reservoir refill probability increased. That is, flood control benefits decreased as water supply and hydropower risks decreased. Refill probabilities between 90 and 99% were recommended (USACE 2002).

The Sacramento Area Flood Control Association (SAFCA) recently investigated the possible benefits of adding forecasts to existing rules; a preliminary study by MBK Engineering (2012) compared the results of including 12-hour, 24-hour, and 48-hour perfect forecasts. With perfect forecasts, flows were reduced to channel capacity. Longer forecasts increased the drawdown prior to the main flood inflow peak. The study concluded that forecasts were beneficial in reducing peak flows but also emphasized that forecast uncertainty should be included in the rule logic when it is better characterized.

In a 2004 study, Bowles et al. detail a reservoir release forecast model for risk-based operation at Folsom. The decision support system (reservoir release forecast model, RRFM) can be implemented in a real-time operational mode or in an off-line planning mode which can include forecast uncertainties. Before the current reoperation study, RRFM simulated current flood operating rules with a Monte-Carlo approach to incorporate forecast uncertainty. The study emphasized the importance of the decision support system functionality during "communication blackout" conditions. Operation during communication blackout requires simple, easy to follow computations which can be performed at a moment's notice, and which can be charted or otherwise documented in the reservoir operations manual alongside the guide curve. If computer or telephone systems are down during an event, the reservoir operator would still be able to make an appropriate decision (Bowles et. al 2004).

Short-term forecast-coordinated operation is also being simulated and implemented in the Yuba River and Feather River watershed. Oroville and New Bullards Bar, two reservoirs in the system, are operated in parallel by two different agencies. The program's goal is to improve communication and the use of forecasts so flood operations release water from the reservoirs earlier and reduce peak flows (Yuba County Water Agency, 2005). In this system, forecasts downstream are affected by reservoir release decisions and so communication between the forecasters at RFC and the reservoir operators must inform both parties' decisions. Release forecasts are proposed by HEC-ResSim and can then be overridden by the reservoir operator, who would communicate the forecasted release to the RFC and operators elsewhere in the system.

Lake Shasta is another reservoir which implements forecast-based operations. The water control manual includes a release schedule based on actual or forecasted inflow, without specifying the time-window of the forecast or addressing the uncertainty of the forecasts (USACE, 1977). Figure 1 shows this release schedule. The operator is given some flexibility to include operations based on forecasts, while a "lights-out" version using only actual inflows is also included. The Bureau of Reclamation has suggested a similar use of forecasts at Folsom which would use the same scheme but would adjust releases based on the forecast time window—a 72-hour forecast would prescribe a lower release than a 12-hour forecast predicting the same peak. Forecast thresholds and corresponding releases have not yet been provided by BOR or approved by USACE.

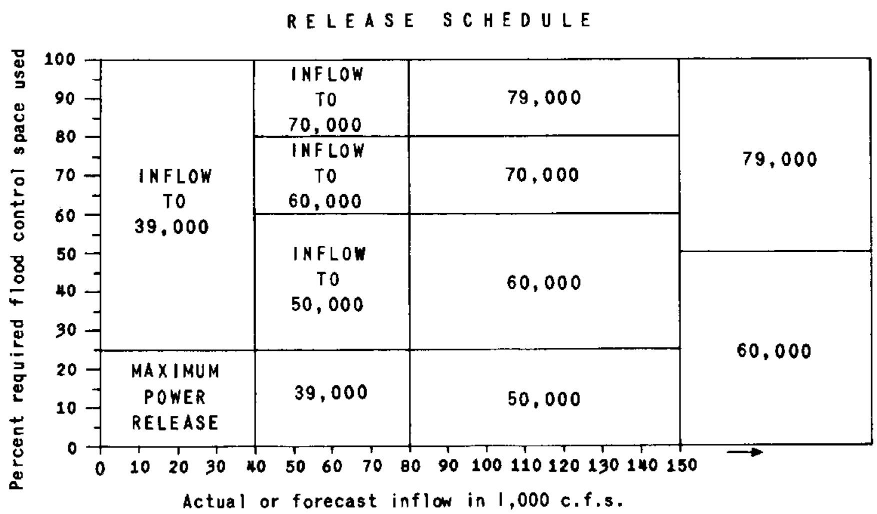

Figure 1. Shasta Release Schedule, 1977 Water Control Manual.

From review of existing literature, three conclusions can be made. First, Folsom is a promising opportunity to test and implement forecast-based operation. Although the proposed use of short-term forecasts is unprecedented, very limited forecast operations elsewhere have been successful, and initial studies at Folsom have shown potential benefits. Second, the rule must be practical and simple enough to comprehensively include in the control manual, while still using information dynamically. Finally, the uncertainty in the forecasts must be incorporated into the rule to mitigate the risk of false alarms.

This study extends the work of others to further specify the uncertainty of the forecasts, implement forecast operations such as developed by HEC (USACE 2002) into the subsequently developed ResSim model, examine how the rules can be used for real-time operations, and assess how the variety of starting conditions and forecast errors affect the function of the proposed rules.

3.3. Hydrologic and Operational Uncertainty

Design of reservoir operating rules is complex due to uncertainty in the data and models used. To assess the risk or protection for a given set of operations, estimates of flood frequencies must be made. A "1-in-200 year flood" or "200-year flood" is a flood which, probabilistically, has a 0.5% (1/200) chance of being exceeded in any given year. The term describes the flood's likelihood of occurring, rather than the expected length of time until another flood of this magnitude arrives. Due to the nature of statistics and probability, a 1-in-200 year flood *could* occur in consecutive years or even twice in one year, although the likelihood of a 1-in-200 year flood occurring in consecutive years is extremely small (1-in-40,000).

Uncertainty in flood frequency estimation adds additional complexity to operations. Flood frequencies are typically based on assumptions of stationarity (the assumption that system conditions do not significantly change over time), that the period of record is an adequate and representative sample, and that large events can be extrapolated. In fact, systems are almost never stationary, and sample sizes are never large enough to capture the variability of the system. Estimates of levels of protection such as 200-year and 500-year are thus constantly shifting targets, updated as more years of information are added to the analysis and as watershed conditions change.

The design of operational rules is further complicated because a given precipitation event can be alleviated or exacerbated by different phenomena and initial conditions. In California's Central Valley, some factors which affect the shape and magnitude of the event include varying snow-pack conditions, basin wetness, timing and depth of the precipitation, and condition and operation of reservoirs upstream. For example, a late-season rain event on a dry basin with little remaining snow-pack poses less threat than the same event on a saturated basin with a large snowpack and a higher potential for snowmelt. A rain event on a basin where reservoirs are already filled to capacity will have more effect than a rain event with empty reservoirs. These phenomena change with climate, further increasing the uncertainty.

Flood hydrographs have many shapes; some have sharp peaks, some have two or more peaks, and others have a large volume over a long duration. Operating rules must be prepared to deal with all possible shapes, not just an average shape. To represent a range of possible hydrographs which could occur at Folsom, USACE Sacramento District uses 6 historical hydrograph shapes with the 3-day unregulated volume scaled to different estimated return intervals ranging 2-year floods to 500-year floods. The use of different hydrograph shapes can also lead to uncertainty as a result of the method used to scale the hydrographs. A shape scaled to a 200-year peak may not correspond with the same shape scaled to a 200-year 3-day volume, and a shape scaled to a 200-year 3-day volume may not correspond with the same shape scaled to a 200-year 1-day volume. Out of the unregulated 1-day, 3-day, 4-day, 5-day, 7-day, 10-day, and 15-day volume scalings, 7-day and 3-day durations were found to generate the highest peak regulated outflow for the current operating set, and preliminary analyses suggested 7-day and 3-day to be the critical durations which represented the 200-year volume at Folsom (David Ford Consulting Engineers, 2011).

More recent studies by the USACE indicated that early computations of critical duration based on highest regulated release did not characterize the usage of available reservoir space (Walker 2013). Rather than directly comparing durations by the highest peak outflow, it was suggested to compare durations by the greatest use of storage, since timing of maximum storage often corresponds with the timing of peak outflow. A refined method of critical duration analysis by the USACE calculates the maximum n-day volumes $V_{n,max}$, calculates the volume $V_{n,p}$ from the beginning of the n-days to the time of peak storage, and then determines the ratio of $V_{n,p}$ to $V_{n,max}$ for each n. The critical duration is the length of time n which leads to a ratio closest to 100%--the length of time that leads to the greatest use of available storage in the reservoir. The ratio was highest for the 2-3 day durations; that is, the reservoir filled more with the scaled 3-day volume than it did with the scaled 7-day volume. With the scaling of hydrographs to 200-year 7-day volumes, the entire space available in the reservoir across 7 days was not used and so the 7-day volume was determined to be too conservative (Walker, 2013). Thus, the USACE Sacramento District estimates return period based on the 3-day unregulated volume and scales the unregulated hydrographs appropriately up or down.

Operations must balance multiple and conflicting objectives, must perform well for a variety of initial conditions and hydrograph shapes, and must be able to incorporate new information or updates in the forecasted conditions of the watershed. Reservoirs thus have inherent operational uncertainties, even without the addition of forecasts. Due to the infinite varieties of possible inflow patterns, one peak inflow does not necessarily correspond to one predictable outflow.

The experience and intuition of the reservoir operator play a large role in real flood operations, since the operator cannot always wait until new information is available to make a release. Even if the available information is incomplete or conflicting, a timely decision must be made. Certainty is never 100%; operational uncertainty remains even after the rules have been set. No simulation model can ever capture the full logic and tradeoff decisions made by a human reservoir operator.

4. Forecast Data

The National Weather Service River Forecast Center provides several forecast products. These include long range ensemble forecasts and short term, 5 day forecasts. Each product and forecasting method is subject to forecast error. Before the products are used, these forecast errors must be quantified. In addition, forecasts and hindcasts are only available for events which have already occurred; since USACE is often concerned with larger events which have not yet happened, artificial forecasts must also be created which mimic the characteristics of true forecasts.

4.1. Error Analysis of Forecasts

Historical 5-day forecast data was available for 6 events between 1997 and 2008 (Appendix A). The limited available data were analyzed to determine whether forecast error (Equation 1 and Equation 2) varies with forecast lead-time, whether error varies for forecasts made closer to the true hydrograph peak, and whether error varies with the magnitude of the event. In addition, the standard deviation of the ratio of forecasted peaks to actual peak (Equation 3), the serial correlation of ratio of the peaks of subsequent forecasts to the actual peaks (Equation 4), and the standard deviation of forecasted peak timing were estimated from historical forecast data. It was necessary to describe the statistics of the ratios in addition to the absolute error because the model used to simulate artificial forecasts (to be described in Section 4.2) will create a random sample of ratios, based on the statistics, to scale 72-hour segments of hydrographs into artificial forecasts. It was also necessary to demonstrate the uncertainty so forecast-based releases could be appropriately limited (to be described in Section 5.3.3).

Equation 1

$$\text{Forecast Error} = (Q_{forecasted} - Q_{actual})$$

Equation 2

$$\text{Percent Forecast Error} = (Q_{forecast} - Q_{actual})/Q_{actual}$$

Equation 3

$$\text{Standard Deviation of Ratio} = \sqrt{\frac{1}{N-1}\sum_{i=0}^{N}\left((V_{forecast,i}/V_{actual,i}) - (V_{forecast,avg}/V_{actual,avg})\right)^2}$$

$$\text{Where } \frac{V_{forecast,avg}}{V_{actual,avg}} = \frac{1}{N}\sum_{i=0}^{N}(V_{forecast,i}/V_{actual,i})$$

Equation 4

Serial Correlation of Ratio =

$$\frac{\sum_{i=0}^{N}\left(\left(\frac{V_{forecast,i}}{V_{actual,i}}\right)-\left(\frac{V_{forecast,avg}}{V_{actual,avg}}\right)\right)\left(\left(\frac{V_{forecast,i+1}}{V_{actual,i+1}}\right)-\left(\frac{V_{forecast,avg}}{V_{actual,avg}}\right)\right)}{\sqrt{\sum_{i=0}^{N-1}\left(\left(\frac{V_{forecast,i}}{V_{actual,i}}\right)-\left(\frac{V_{forecast,avg}}{V_{actual,avg}}\right)\right)^2\sum_{i=1}^{N}\left(\left(\frac{V_{forecast,i}}{V_{actual,i}}\right)-\left(\frac{V_{forecast,avg}}{V_{actual,avg}}\right)\right)^2}}$$

4.1.1. 3-day vs 5 day Forecasts

Forecasts for events which are further in the future are expected to be less accurate than forecasts of closer events—the flow forecasted 24 hours from now is likely to be predicted with less error than a flow forecasted 3 days from now. Carpenter and Georgakakos (2003) analyzed error for precipitation forecasts for 1998-2003 on the American River Basin as (observation – forecast). Error of the precipitation forecasts remained constant over 3 days, although standard deviation of error increased. They found that error increased between 3 and 5 days and the standard deviation of error remained constant between 3 and 5 days. Serial correlation decreased dramatically between zero and 24 hours. These signs all indicate that forecast reliability decreases after about 3 days. The study concluded that precipitation forecasts were most useful for the first 48 hours. Since there were no 100- or 200-year events in the short record, and the analysis focused on precipitation forecasts rather than flow, the authors also recommended that more studies be completed on Folsom’s operational forecasts as information becomes available.

To determine whether the forecast error for flow actually increased with the lead-time of the forecast, the flow forecasts for the largest events between 1997 and 2008 were analyzed. The average error in forecasted peaks and the standard deviation of error in forecasted peaks were plotted against forecast length (Figure 3 and Figure 3).

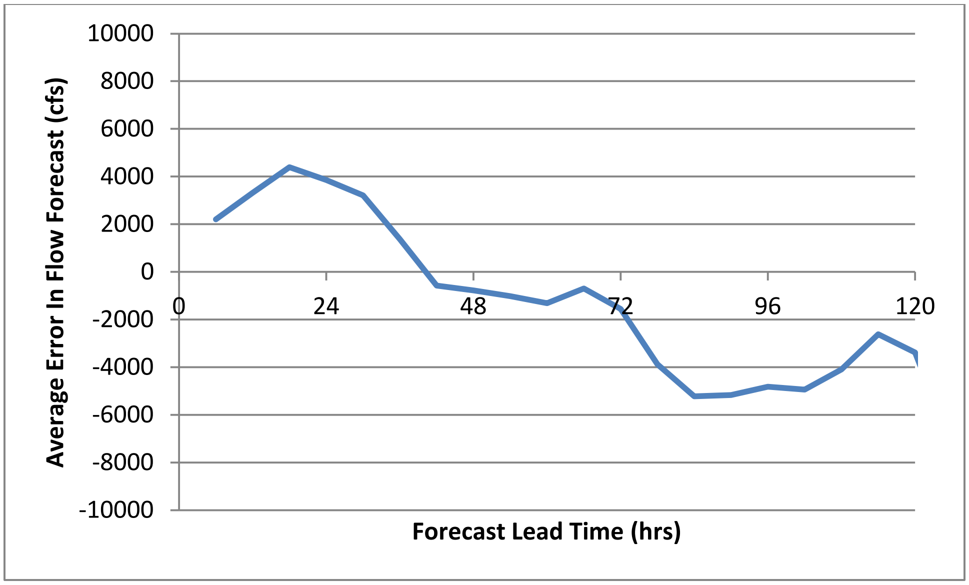

Figure 2. Average Absolute Error Vs. Lead Time

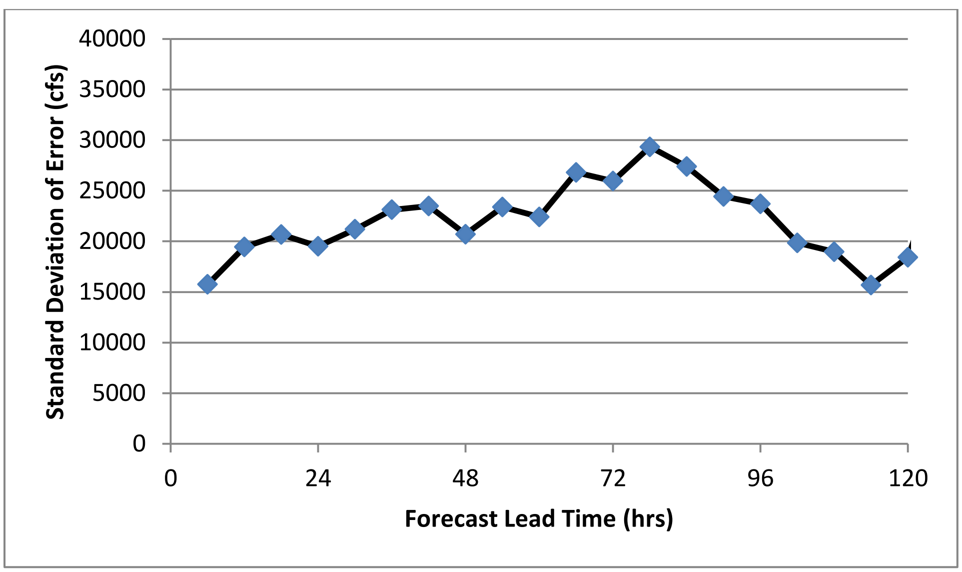

Figure 3. Standard Deviation of Absolute Flow Error vs lead time

The average of errors plotted against lead time indicates that the forecasted peaks were typically between 5000 cfs too high or 5000 cfs too low from the true peaks (Figure 2), with a rise in error in the first 24 hours. For the first 24 hours, the positive error indicates that forecasts were typically overestimates, and for 48-72 hours onward the negative error indicates that forecasts were underestimates (Figure 3). Meanwhile, the standard deviation of error rose steadily for lead times between 0 and 72 hours, and began to drop after 72 hours (Figure 3).

Forecasts after 48 to 72 hours appear to be conservative estimates of the actual flows, and results for flow forecasts did not demonstrate a notable increase in error between 3 and 5 days. Estimates may grow increasingly more conservative with lead time due to low forecasts from the forecasting model (lack of skill) or adjustments to account for uncertainty based on forecaster's judgment (*perceived* lack of skill). The increasing standard deviation of error points to this increasing uncertainty in the skill.

Since the average error of flow forecasts did not noticeably increase between 3 and 6 days, results were therefore not entirely consistent with the findings of Carpenter and Georgakakos (2003) for precipitation forecasts; other factors such as larger event size, different forecast spacing, and different forecast time periods may have affected the results. However, the standard deviation of error for flow forecasts did increase, similar to Carpenter and Georgakakos' findings for precipitation forecasts.

4.1.2. Forecast Error and Serial Correlation of Peaks

Forecast error may not be constant for different sized events, since some types of storms may be more or less difficult to forecast and since forecasts for smaller events are not updated as often. For each event, the ratios of peak flow to actual flow were computed for the 5 day period before the true peak. The standard deviation of this series of ratios is plotted against the event peak in Figure 4.

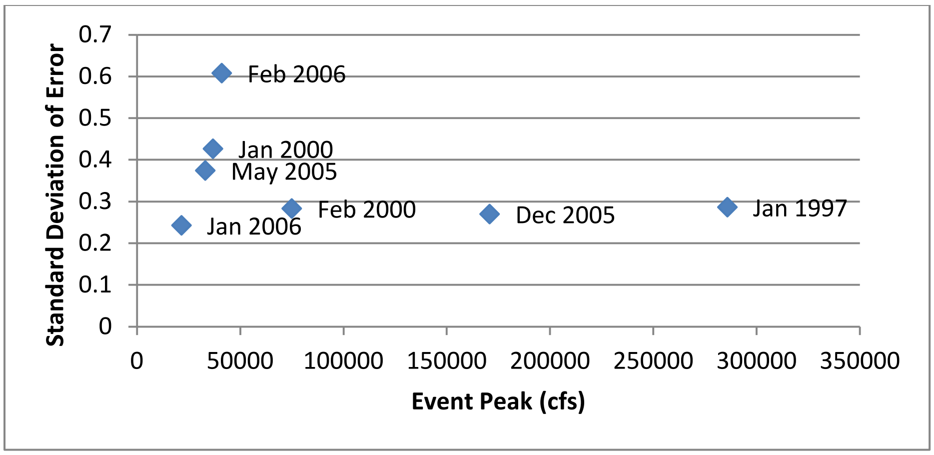

Figure 4. Standard Deviation of Ratio vs. Event Peak.

The data do not indicate a clear trend for the small peaks (~50,000 cfs). The standard deviation of error is smallest, and appears to remain fairly constant, for the three largest peaks. More observations will be needed to verify this result.

Next, the serial correlation of the series of ratios was computed to assess if each individual forecast was similar to the forecast before and after it. Since each event had different forecast spacing (ranging from 6 hours between forecast to 14 or 24 hours between forecasts), the serial correlation was different for each. Generally, serial correlation increased with event size and decreased with increasing time between forecasts, as expected. Closer-spaced forecasts for larger events are more likely to be similar from forecast to forecast. Figure 5 and Figure 6 demonstrate the overall trend of the serial correlations.

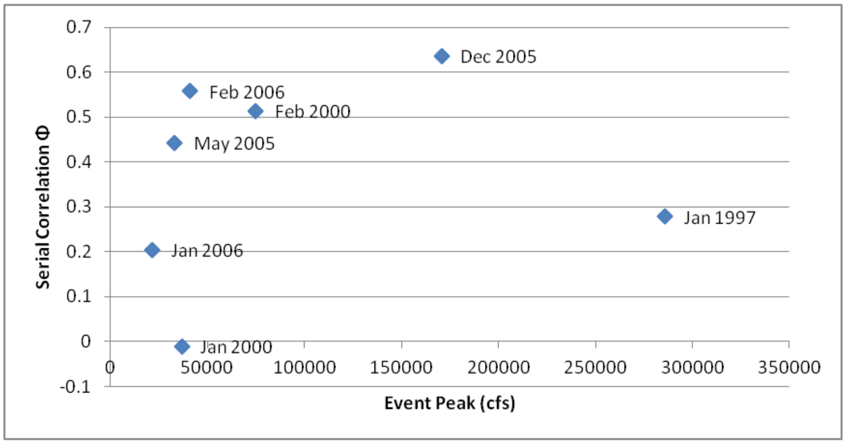

Figure 5. Serial Correlation of Ratio vs Event Peak

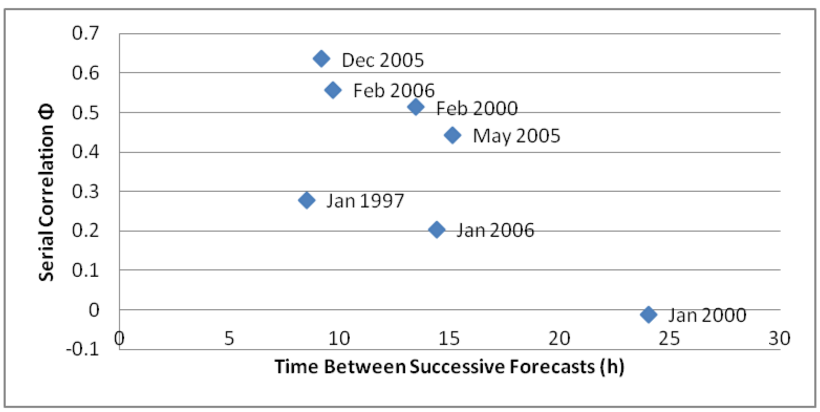

Figure 6. Serial Correlation of Ratio vs. Forecast Spacing

The serial correlation for January 1997, the largest and most relevant event to the problem being studied, appears not to follow the same trend as the other events. This could result from the event being caused by an atmospheric river while the other, smaller events were caused by other climatological phenomena; in addition, CNRFC suggested that snow pack at lower elevations may have been under-simulated, and that the high rain intensity during the 1997 event may have affected the tipping-bucket gauges, causing undercatch. (RFC, 2005 and Biddle and Duchon, 2010). The serial correlation could also be low relative to the other events because the 1997 event has the oldest set of forecasts and forecast models have improved since 1997.

The CNRFC is currently developing a set of hindcasts for the full period of record; these hindcasts will provide information about what the forecast would have been for each event, had the forecast technology been available at that time. For the following reasons, the set of actual forecasts is inconsistent, and only limited conclusions can be drawn: (1) in 1997 and 2000, different forecast methods were used than in 2005 and 2006, and (2) each set of actual forecasts had different spacing, often irregular, with forecasts being issued as few as 5 hours and up to 24 hours apart. Therefore, if the same forecast method is used for all hindcasts, and the hindcasts are more regularly spaced, it is possible that the hindcasts would show more consistent serial correlations and a more pronounced trend of error standard deviations. Hindcasts will provide improved insight into other errors, such as false alarms, and will be crucial for estimating the skill of the forecasts. No information is currently available about the rate of false alarms, forecasts which predict an event which never happens, although information about false alarms is very important for forecast-based rules to minimize unnecessary large releases.

Until hindcasts are available, a serial correlation of 0.5 will be assumed, based on the average of results from the 3 largest events. The average standard deviation of these 3 events is 0.28. A summary of the statistics for all events is listed in Table 1.

Table 1. Summary of Event Statistics.

	Peak Flow	Phi	Sigma		
	Cfs	Serial Correlation of Peak Error Ratio	Standard deviation of Peak Error Ratio	Average Time Error (hours)	Standard Deviation of Time Error (hours)
January 2006	21627	0.20	0.24	3	3
May 2005	33144	0.17	0.37	-23	31
January 2000	36868	-0.01	0.43	16	10
February 2006	41113	0.56	0.61	-13	9
February 2000	75000	0.51	0.28	4	5
December 2005	170794	0.64	0.27	30	37
January 1997	285922	0.28	0.29	-22	25
Average		0.34	0.36	-1	20
Average of top 3		0.48	0.28	4	22
Suggested		**0.5**	**0.28**	**0**	**9**

4.2. Developing Artificial Forecasts

Artificial forecasts were needed to simulate the synthetic hydrographs and to evaluate potential sets of forecasts other than those that actually occured. The approximate statistics (Section 4.1.2) were used to roughly simulate these artificial forecasts. Forecasts were simulated using a suggested method from USACE (2002), as follows: The inflow hydrograph was first shifted by a random time factor $\tau(i)$; the first forecast's time shift factor was largest to reflect greatest error in predicting the date of the peak (Equation 5). The time-shift for subsequent forecasts gradually decayed to zero error in predicting the date of the peak. After the time shift, each shifted hydrograph was scaled upward or downward by another random factor, factor(i). The random factors were generated as a lag-1 autoregressive function from the serial correlation and standard deviations (Equation 6). This process was repeated for several consecutive 5 day time windows to generate a set of forecasts for an event, with forecasts starting 72 hours in advance of the event hydrograph to be simulated.

Equation 5

$Q_f(i,t) = Q(t + \tau(i)) * \text{factor}(i)$

where: i is an individual forecast out of the set of forecasts for the event

and $\tau(i)$ = time shift for forecast i.

Equation 6

$\text{factor}(i) = \mu + \hat{\phi}(\text{factor}(i-1) - \mu) + \varepsilon(i)$

where: $\mu = 1$,

$\hat{\phi}$ = serial correlation of successive factors

$\varepsilon(i) \sim N(0,\sigma_\varepsilon)$ = random error in member of AR(1) series

$\sigma_\varepsilon^2 = \hat{\sigma}^2(1 - \hat{\phi}^2)$

The parameters $\hat{\phi}$ and $\hat{\sigma}$ used were 0.5 and 0.28, chosen from the average of the top 3 available historical forecasts. Select synthetic forecasts are provided for reference in Appendix B. As each successive forecast predicts a different peak, the peak 3-day forecasted flows and volumes change; summaries of these changing forecasted peak volumes and flows are provided alongside the synthetic forecasts in Appendix B.

The method used to generate artificial forecasts cannot perfectly capture the characteristics of actual forecasts for the event for several reasons: the statistics describing the actual forecasts are limited to a small sample size, especially for a 200-year event or larger; and the method used to generate them "reset" the decaying time error for subsequent forecasts after an arbitrary amount of time—5 days—instead of allowing the time error to decay throughout the entire 30-day window. The arbitrary reset was chosen to prevent the forecasts from becoming "too perfect" due to the time error decay towards the end of the 30-day simulation. Arbitrary reset also helped to simulate the fact that the forecasts are never consistently late or consistently early throughout the entire event. Had the time error not reset after 5 days, the entire set of forecasts would still have been skewed early or late.

5. Simulation Strategy

5.1. Existing ResSim Model

The new forecast-based operating rules were simulated and evaluated using the USACE Hydrologic Engineering Center Reservoir System Simulation (HEC-ResSim) model, using the USACE's most recent set of flood control operating rules. The USACE provided period-of-record hourly inflows for water years 1922 to 2002 as well as a set of 6 scaled and synthetic events ranging from the 1-year flood to the probable maximum flood (PMF). Of these, only the 200-year scaled events were selected for simulation and rule demonstration since the stated objective of the Joint Federal Project is a 200-year level of protection; existing operations already pass 100-year floods safely. Based on the decision to use 200-year event shapes for rule demonstration, the artificial forecasts mimicking RFC model 6 hour, 5 day forecasts for each of the 200-year event shapes were also used as input to the HEC ResSim model. Artificial forecasts are shown in Appendix B.

The existing ResSim model contains an operations set with groups of rules for 7 zones in the reservoir; the zones primarily of interest are the flood control and conservation zones. The three rules which guide release decisions in the flood control zone are as follows:

1.) Fish and Wildlife Service Mitigation rule—limits release to maximum of 50% of previous timestep's inflow, 60% of 12 hour forecasted inflow, or the previous timestep's outflow. The rule is active up to releases of 90 kcfs.
    If Q_{in} <150000 and El < 466,
    $Q_{out,current} < \max(0.5*Q_{in,previous}, 0.6*Q_{in,forecasted,12hr}, Q_{out,previous}, 90000)$
2.) Accelerated transition Rule—uses 12-hour projected inflows and current inflow to step release rates up and down between 115 kcfs and 160 kcfs.

3.) Table 2 shows the release schedule for the Accelerated Transition Rule.

Table 2. Accelerated Transition Rule in Existing ResSim Model

$Q_{in, previous}$ \ $Q_{in, projected,12hr}$	>160,000 cfs	>360,000 cfs	>370,000 cfs
>115,000 cfs	115,000 cfs	115,000 cfs	115,000 cfs
>200,000 cfs	115,000 cfs	130,000 cfs	130,000 cfs
>250,000 cfs	115,000 cfs	145,000 cfs	145,000 cfs
>270,000 cfs	115,000 cfs	145,000 cfs	160,000 cfs

4.) Smoothing Rule—ensures that releases do not oscillate. Prescribes release based on rising and falling elevations and inflows; rise and percent of encroachment; specific inflow vs. outflow ordinates; and specific elevations, encroachment levels, or ranges. (Table 3)

The existing Accelerated Transition Rule and Fish and Wildlife rule do not incorporate 12-hour forecast inflows from RFC; they route water which has *already fallen* higher in the watershed, and which will take 12 or more hours to arrive at Folsom. The simulation model uses actual inflows with a 12-hour lookahead to approximate this routing. Proposed forecast rules would incorporate additional forecast information, such as information provided by the RFC.

As specified in the most current reservoir operations manual (USACE 2004), the Emergency Spillway Release Diagram (ESRD) supersedes these three rules, and guides releases during events large enough to threaten the integrity of the spillway and dam. The ESRD sets outflows based on inflow and current elevation (Figure 7).

Table 3. Smoothing Routine in Existing ResSim model

Flood Zone	Pool (past 4 hr)	Inflow (past 4 hr)	Pool Elev (past hr)	Encroachment	Inflow (Past hr)	Outflow (Past hr)	Max Outflow (Past 72hr)	Encroachment Level %	Release
Encr	Rising	Rising		Rising	<= Max Inflow (Past 72hr)				minimum (115000, maximum(Inflowpast 4 hrs, Outflowprevious))
Encr	Rising	Rising		Rising	>Max Inflow (Past 72hr)				Outflowprevious
Encr	Falling	Rising				<=210kcfs			minimum (Outflowprevious , maximum (Inflowprevious * 1.25, 115000))
Encr	Falling	Rising				>210 kcfs			minimum (Outflowprevious , maximum (Inflowprevious * 1.25, 50000))
Encr	Rising	Falling	<=466'						Outflowprevious
Encr	Falling		>=448'			>Inflow (past hr)	<=210kcfs		minimum (Outflowprevious, maximum (Inflowprevious * 1.25, 115000))
Encr	Falling		>=448'			>Inflow (past hr)	>210 kcfs		minimum (Outflowprevious, maximum (Inflowprevious * 1.25, 50000))
Encr	Falling	Falling						20-50	round(minimum (Outflowprevious, maximum (Inflowprevious * 1.25,((Storageprevious - Storageprevious TOC)*12.1+inflow_24)/24)),-3)
Encr	Falling	Falling						0-20	round(minimum (Outflowprevious, maximum (Inflowprevious * 1.25,((Storageprevious - Storageprevious TOC)*12.1+inflow_48)/48)),-3)
Encr					<=15 kcfs			5-10	minimum (maximum (8000, Inflowpast 4 hrs), Outflowprevious)
Encr					<=8 kcfs			1-5	minimum (maximum (4000, Inflowpast 4 hrs), Outflowprevious)
Encr					<=4 kcfs			0-1	minimum (maximum (2000, Inflowpast 4 hrs), Outflowprevious)
Encr									Outflowprevious
Not Encr									minimum (Inflowprevious, Outflowprevious)

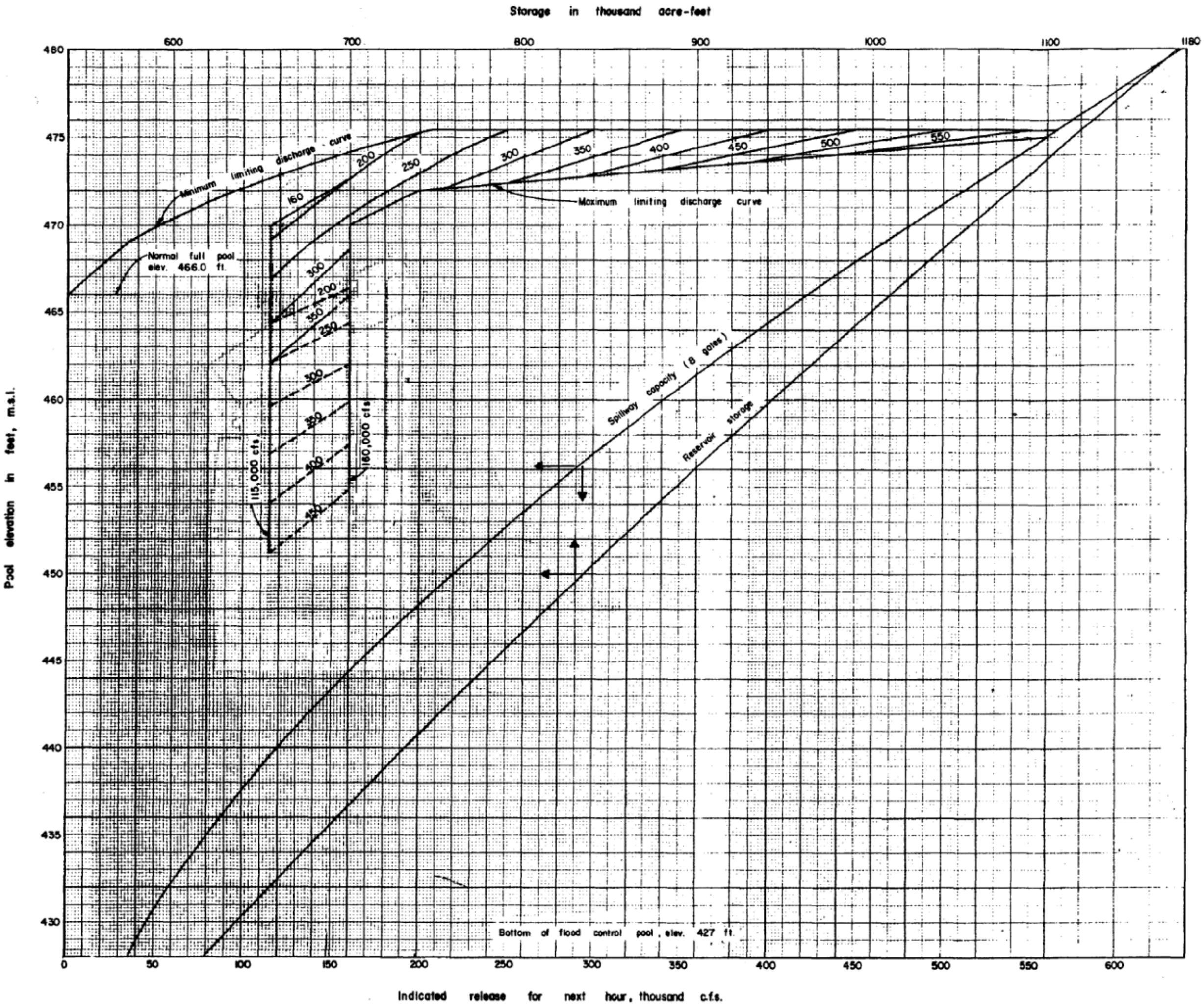

Figure 7. Emergency Spillway Release Diagram

5.2. Operations without Forecasts

To demonstrate the performance of the existing rules, and to determine where operational improvements can be gained, the hydrographs and operations set provided by USACE were routed through the reservoir with two starting conditions and without forecast based release. Figure 8(a) through 8(l) show the routing without forecasts.

To maximize water storage, USACE currently reduces Folsom's flood pool when the upstream reservoirs at Hell Hole, French Meadows, and Union Valley have storage available—referred to as "storage credit". Thus the space available in the flood pool can vary between 400,000 acre-feet and 600,000 acre-feet. During a flood event, the flood pool may start with a specified 400,000 acre-feet of empty space, full credits upstream, and TOC at its highest elevation; as the upstream reservoirs fill later in the event, the specified flood pool size increases to 600,000 acre-feet and TOC is at its lowest elevation. TOF and TOC are indicated by dashed lines on the storage plots in Figure 8(a) through 8(l).

(200-year PMF Shape, 600 TAF Starting Storage)

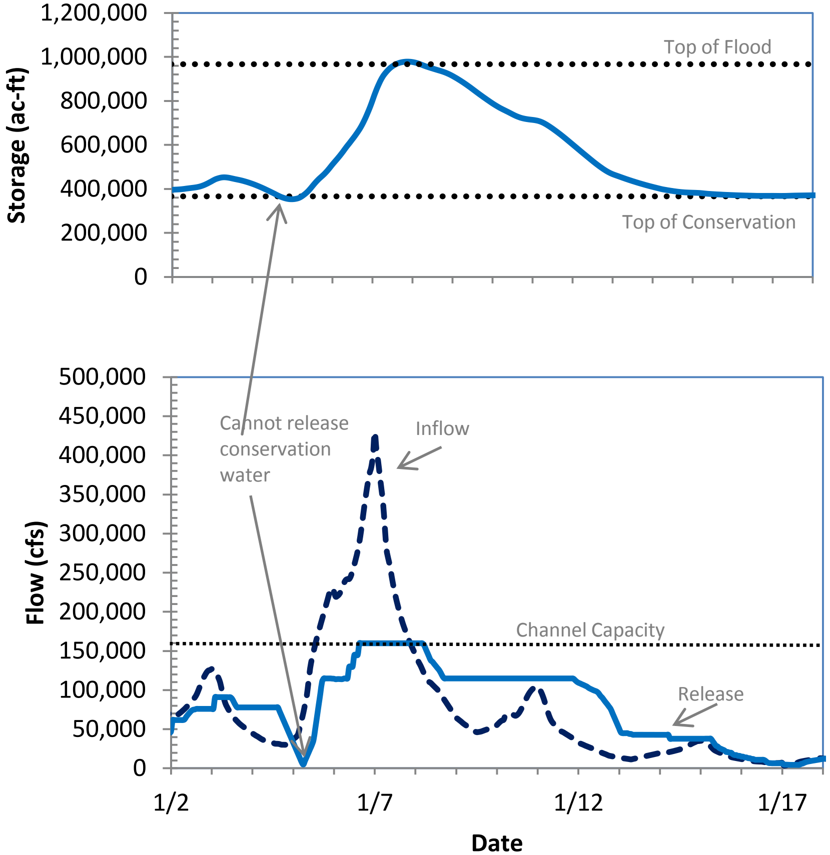

Figure 8(a)

(200-year PMF Shape, 400 TAF Starting Storage)

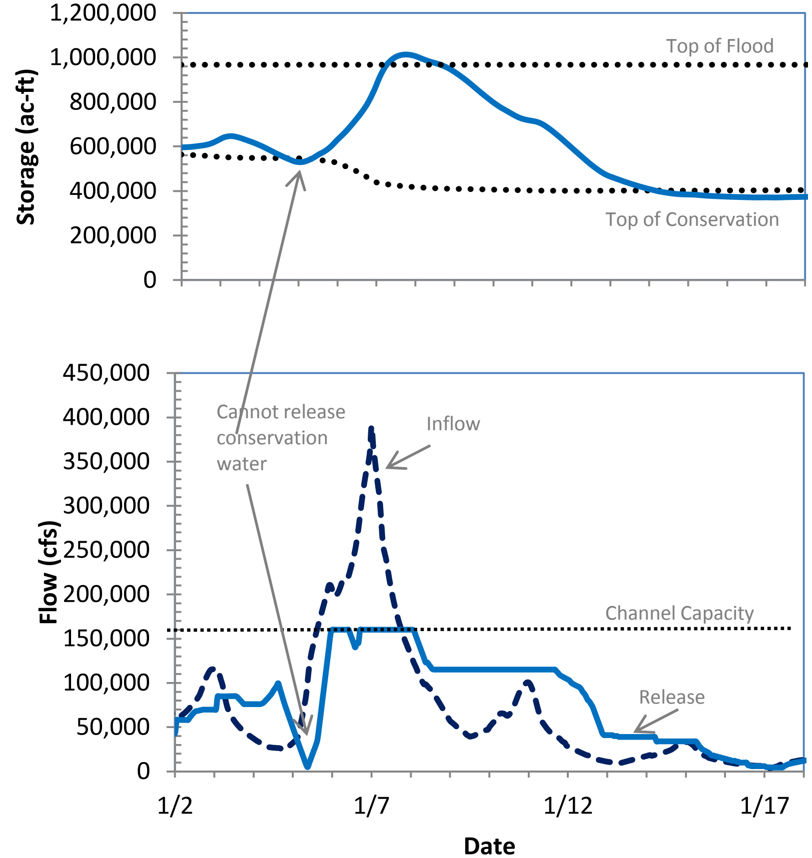

Figure 8 (b)

Figure 8. 1-in-200 year operations-Existing operations set without forecasts

(200-year SPF Shape, 600 TAF Starting Storage)

(200-year SPF Shape, 400 TAF Starting Storage)

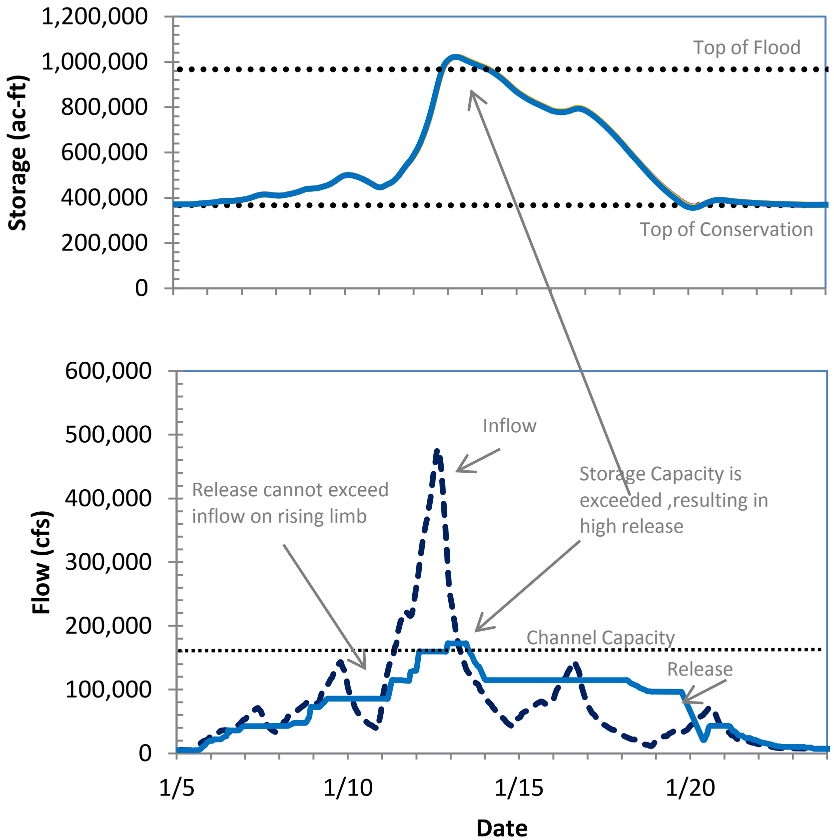

Figure 8 (c)

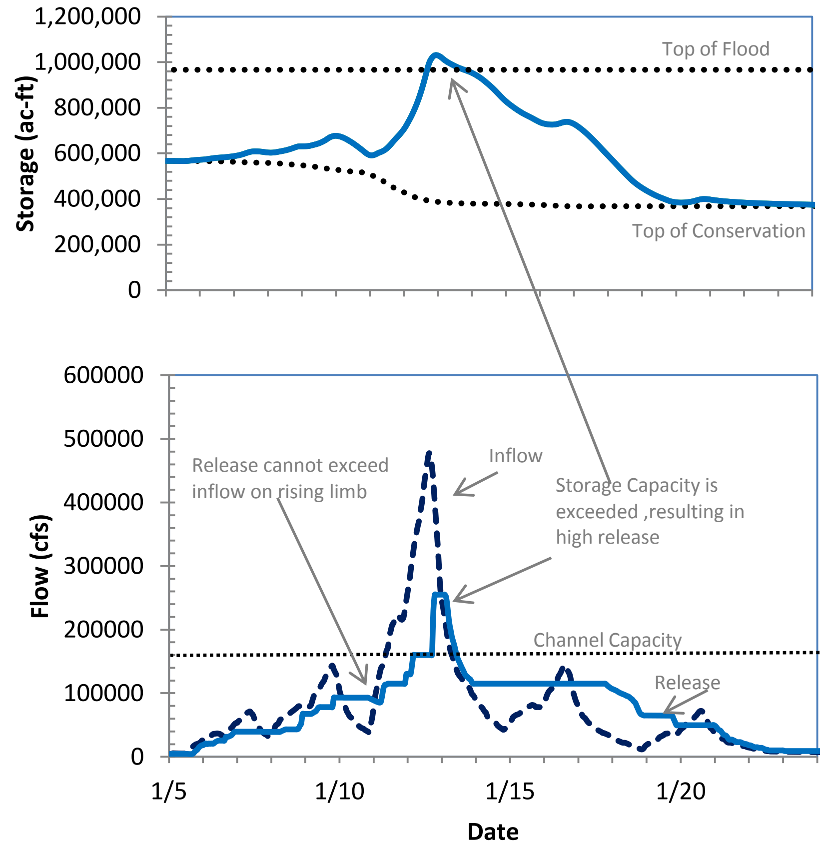

Figure 8 (d)

Figure 8, Continued

(200-year 1955 Shape, 600 TAF Starting Storage)

(200-year 1955 Shape, 400 TAF Starting Storage)

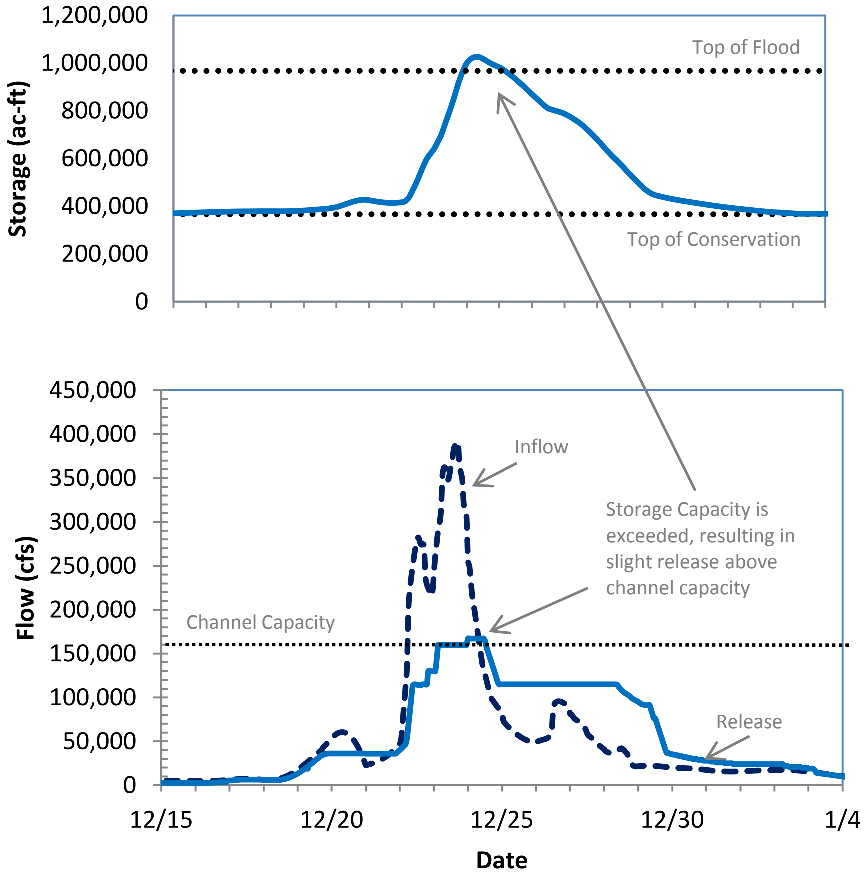

Figure 8 (e)

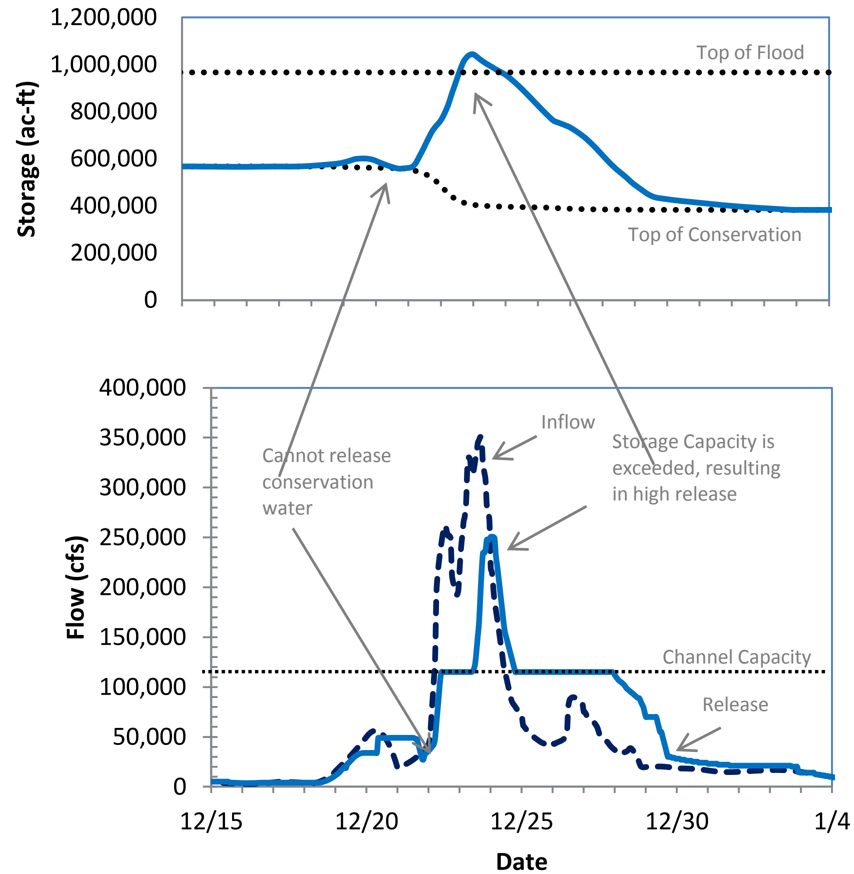

Figure 8 (f)

Figure 8, Continued.

(200-year 1965 Shape, 600 TAF Starting Storage)

(200-year 1964 Shape, 400 TAF Starting Storage)

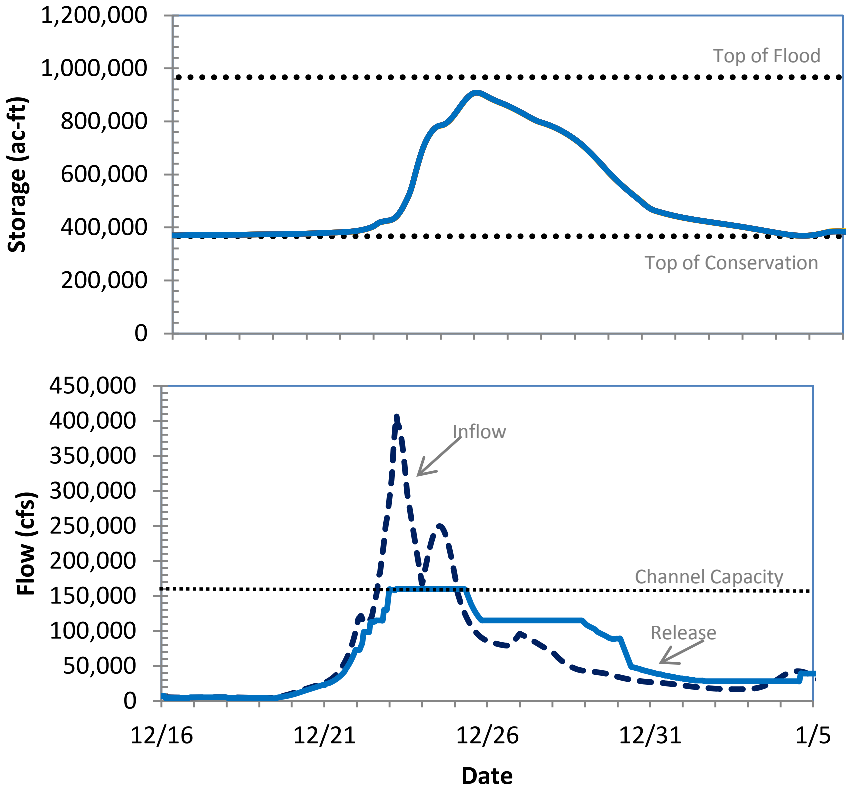

Figure 8 (g)

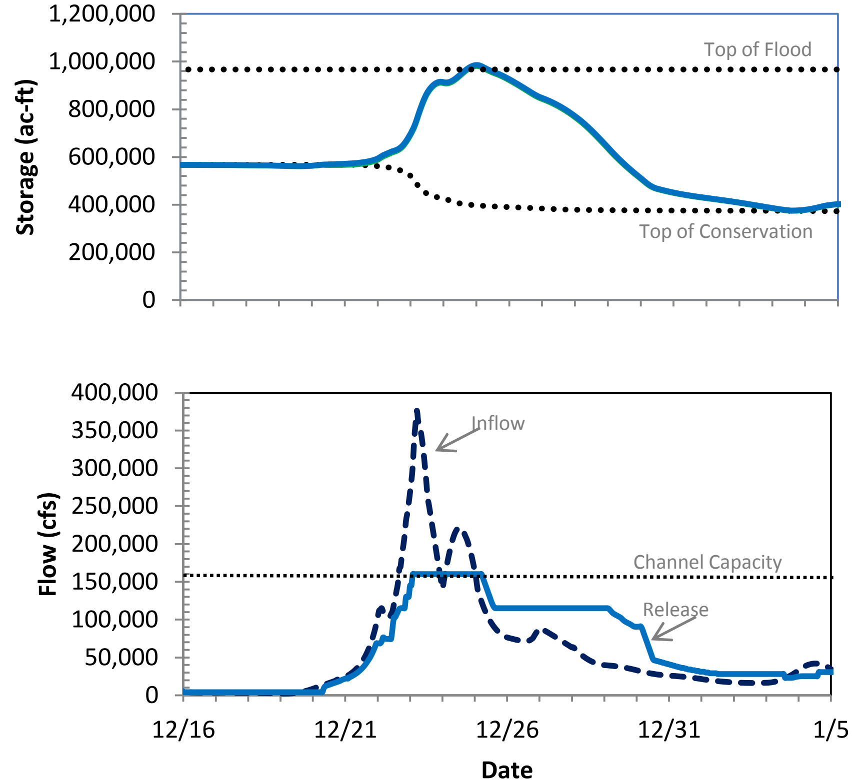

Figure 8 (h)

Figure 8, Continued.

(200-year 1986 Shape, 600 TAF Starting Storage)

(200-year 1986 Shape, 400 TAF Starting Storage)

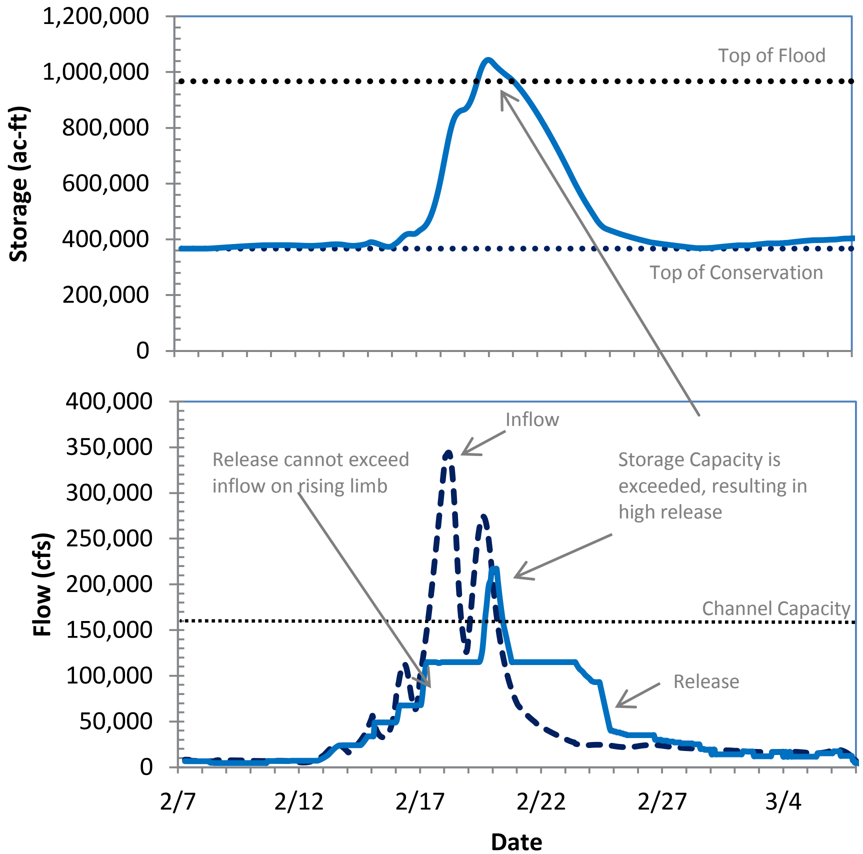

Figure 8 (i)

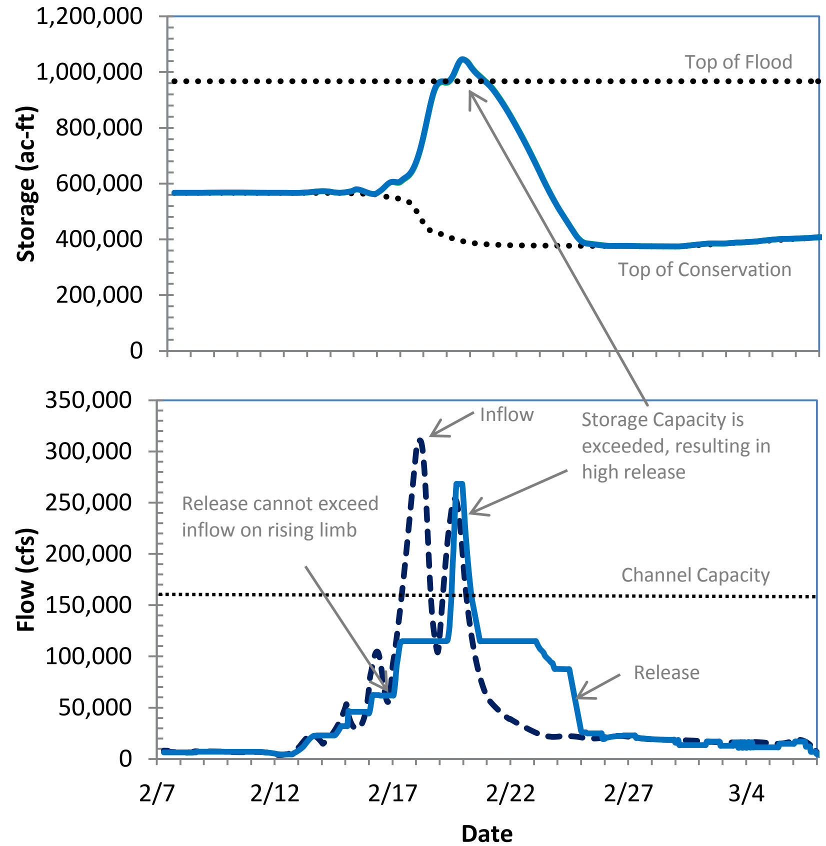

Figure 8 (j)

Figure 8, Continued.

(200-year 1997 Shape, 600 TAF Starting Storage)

(200-year 1997 Shape, 400 TAF Starting Storage)

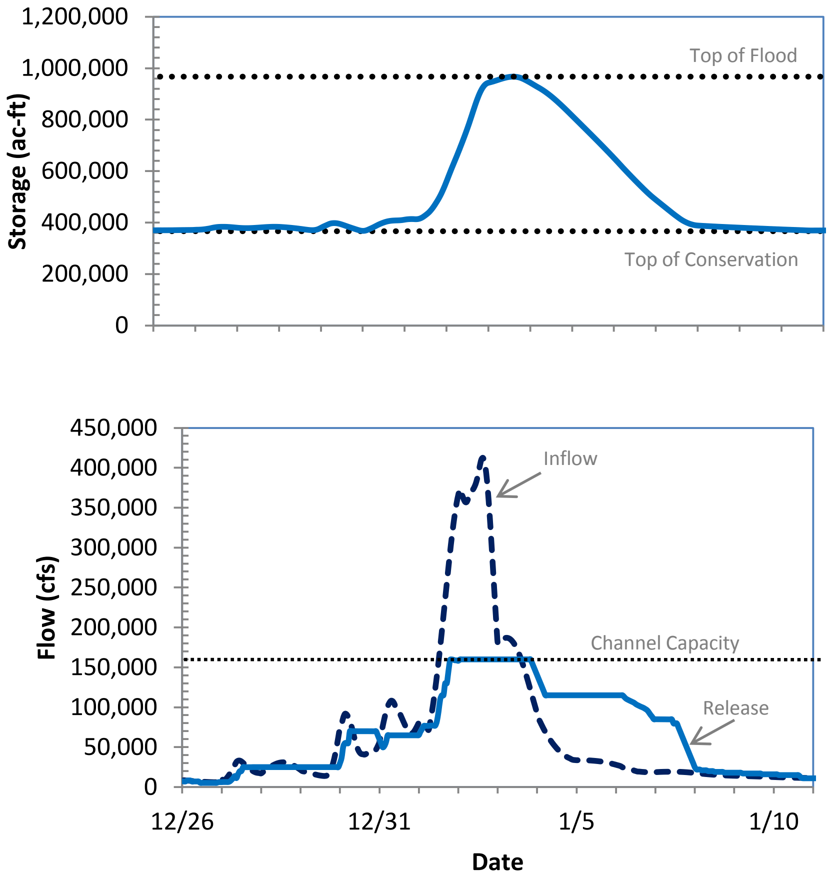

Figure 8 (k)

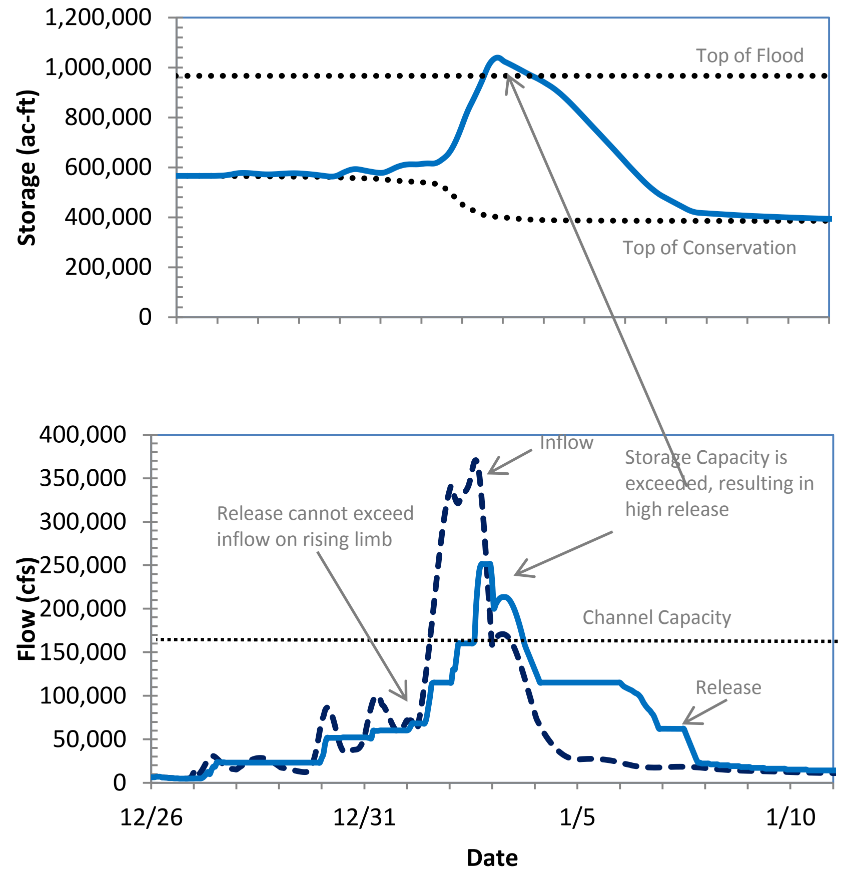

Figure 8 (l)

Figure 8, Continued.

Without forecast-based releases, storage for many of the simulated 200-year events exceeds the flood pool and enters the surcharge zone. In addition, although the peak of the incoming flood wave is significantly reduced in all cases, 8 of the 12 simulations exceeded the channel capacity of 160,000 cfs due to Emergency Spillway Release.

No releases in excess of peak inflow are made, regardless of how slowly or rapidly the hydrograph rises. In addition, releases are sometimes subject to drop when they reach the guide curve (TOC) and inflow is low, even if the hydrograph is climbing steeply. Both PMF-shaped simulations have this behavior between the third and fourth days of the simulation, as the inflow hydrograph begins to climb (Figure 8a and Figure 8b). The 1955 simulation with 400,000 acre-feet initial starting storage behaves similarly near the seventh day of the simulation.

Releases between 0 and 115,000 cfs generally ramp up in slow, smooth plateaus and keep the storage low early in the flood—driven by the smoothing routine and the rate of change rules. Releases plateau at 115,000 cfs until inflow reaches 200,000 cfs and flows at a point 12 hours upstream reach 360,000 cfs. When these conditions are both met, the flows ramp up from 115,000 to 160,000 with the accelerated transition rule.

Eventually, the flood pool fills to TOF if the flood is large enough. As soon as TOF is exceeded, the ESRD initiates releases greater than the 160,000 cfs channel capacity to bring the reservoir storage out of the surcharge zone. Then, to bring the reservoir storage back down to TOC, releases are sustained at 115,000 cfs for 3 to 4 days after the peak release. Releases begin to taper off as the storage meets TOC.

In summary, the current operating strategy is to use the storage until the flood peaks or the flood pool is exceeded, increase releases based on the ESRD if the flood pool is exceeded, and then release the volume of the captured peak after the flood event. However, for large floods, too much water can be stored early in the event, resulting in high flows when storage space in the flood pool runs out (Figures 8c, 8d, 8e, 8f, 8i, 8j and 8l). The proposed use of forecasts would identify when large floods are imminent, and would release some of the volume of the incoming flood *before the peak occurs* in addition to the volume released afterwards. This would require early releases in excess of inflow to be made.

5.3. Proposed Operating Rules

The proposed rules are based on the operating rule presented in the 2002 HEC study (USACE, 2002). With the HEC formulation, each operating rule must state under which forecasted and actual flow conditions and at which reservoir elevations the rule is active-the "start trigger". The rule must also compute the amount to be released, and state whether the release is a maximum (must *not* be exceeded) or a minimum (*must* be exceeded). The rule must be assigned to a zone (primarily to specify whether advance releases may or may not draft below the conservation pool). Finally, the rule must be assigned a priority in each zone relative to other rules in the zone.

5.3.1. Start trigger

The start trigger indicates that a flood is imminent and some action must be taken. The trigger could be based on the peak forecasted volume or the peak forecasted flow. When selecting the start trigger, the probability of false-alarms and the uncertainty in the forecasts must be considered. Should a 200-year flood, a 500-year flood, or some other magnitude trigger the rule? Is the difference between a 200-year flood and a 500-year flood within the uncertainty in the forecasts?

With a start trigger that is too low, advance release would be initiated too early. For large events, the forecasts could lead to an early increase up to channel capacity—which would be undesirable for downstream structures due to the decreased warning time. For small events with too-low start triggers, the probability of unnecessary releases would be greater than for large events because the flood pool is more likely to be able to pass a small event without advance release. Unnecessary releases could reduce water supply deliveries and subject downstream structures to unnecessary risk.

As the start trigger increases, the advance release would be initiated later, and so produce a smaller increase in available storage volume. For large floods, the forecasts would still lead to an advance release up to channel capacity, but the release would be later. The probability of false-alarms and unnecessary releases for a too-high start trigger would be lower. If the trigger is too high, advance release may not initiate early enough to create adequate flood storage capacity.

Three triggers were evaluated:

Low: 200 kcfs forecasted peak flow OR 1,000,000 ac-ft forecasted inflow volume

Medium: 300 kcfs forecasted peak inflow OR 1,000,000 ac-ft forecasted inflow volume

High: 500 kcfs forecasted peak inflow OR 1,000,000 ac-ft forecasted inflow volume

A tiered rule using both high and low triggers would also be possible, and would implement a less aggressive response if the lower trigger was activated but the higher trigger was not activated. The tiered rule was not evaluated. In addition, all of the volume triggers remained constant at 1,000,000 acre-feet. Future studies could evaluate the possibility of tiered rules or varying start triggers based on volume.

5.3.2. Advance Release Rule

Rules that suggest releases prior to the flood would be advance-release rules—designed to draw down the reservoir to create space for the flood. The advance release rule formulated by HEC (2002) is activated when forecasted flow or volume exceeds a specified trigger. When active, the rule evaluates the space available in the reservoir, determines the volume of water entering the reservoir, and begins release of the water that will not fit.

If $Q_{peak} > 300{,}000$ cfs or if $V_{event} > 1{,}000{,}000$ acre-feet:

$$\text{Release} = \max(Q_{out} = V_{peak}\text{-}V_{avail}/(t_{peak} - t_{current}) \text{ or } Q_{out} = V_{event}\text{-}V_{avail}/(t_{event} - t_{current}))$$

Where $V_{avail} = \text{TOF} - \text{Storage}_{current}$

TOF = storage at the top of the flood pool

$Storage_{current}$ = storage at current time step

$t_{current}$ = Date of current time step

t_{peak} = Date of the event peak

t_{event} = Date flow recedes below 115,000 cfs

V_{peak} = Volume to the peak

V_{event} = Volume to time when flow recedes below 115000 cfs

The two computed releases are based on time to peak and total flood duration. The specified minimum release output by the rule must select the maximum of these releases to ensure that the flood volume and the volume to peak are passed safely through the dam. The volume computation V_{avail} depends on whether the objective is to meet the top of the flood zone (TOF) or the guide curve at the top of the conservation zone (TOC). If the objective is to maximize flood pool use, V_{avail} is computed by subtracting the current pool storage from the total storage at TOF. If the objective is to minimize flood pool encroachment, V_{avail} is computed as the negative of the level of encroachment by subtracting the storage at TOC from current pool storage. The rule formulated by HEC (2002) maximized use of the flood pool and calculated V_{avail} from TOF.

5.3.3. Adjustments for Refill probability

The use of forecasts is not without risks and tradeoffs. If a false-alarm occurs and a large event is forecasted which does not materialize, a forecast-based release rule which does not recognize uncertainty and which assumes all forecasts are perfect would release too much water. The unnecessary drafting of the pool could lead to severe consequences downstream such as increased strain on levees from prolonged flows, water supply impacts from water released that is not recovered, hydropower energy spill, and unnecessary impacts to sensitive aquatic species. If channel capacity were exceeded due to forecast error, unnecessary loss of life and damage to structures could occur.

To incorporate forecast uncertainty into the release rule, and to reduce the probability of making unnecessary releases due to false alarm, refill probabilities based off estimated volume quantiles are used. A “volume quantile” reflects the uncertainty around a forecast—the 1% volume quantile is a volume *x* such that the probability of actual inflow volume exceeding *x* is 99%. To describe it differently, a 1% quantile *x* of a forecast would suggest that there would be a 99% probability of at least that inflow volume *x* entering the reservoir, or a 99% refill probability. The term “refill probability” may more aptly be described as a “recovery probability”. By default the forecast-release rules are configured to release water only from the encroached flood pool, and thus the incoming hydrograph would not be “refilling” the conservation pool. Figure 9 (from USACE, 2002) illustrates the concept of volume quantiles and Equation 7 describes how they are computed based on the Normal Distribution.

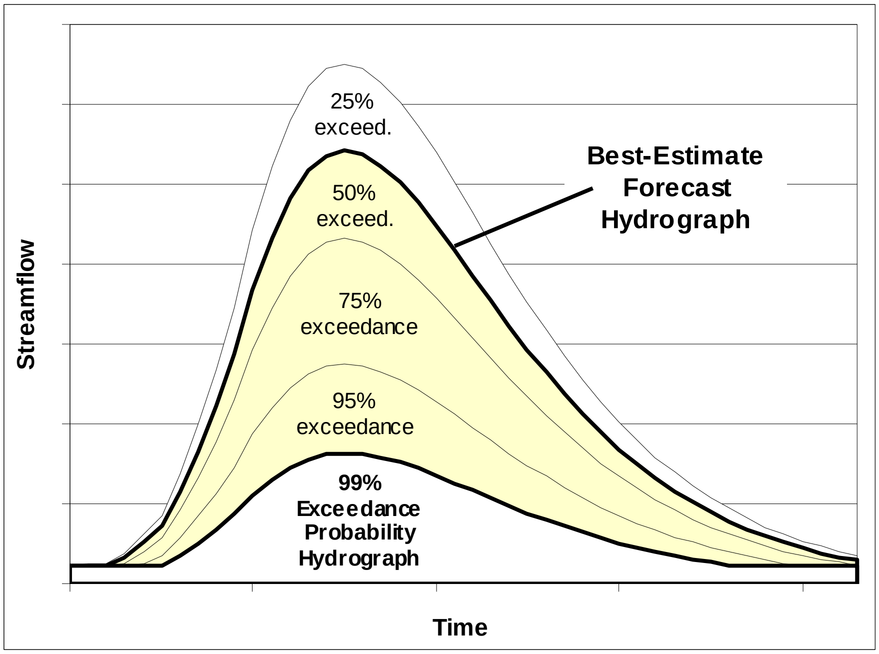

Figure 9. Illustration of Volume Quantiles [USACE 2002]

Equation 7. Computation of Volume Quantiles (based on Normal Distribution)

Volume Quantile $V_\alpha = \mu_{vol}(1 - z_\alpha * \hat{\sigma})$, such that:

$\hat{\sigma}$ = standard deviation of ratio of forecast to actual flow (historical information)

μ_{vol} = best estimate inflow (forecasted)

$z_{0.01} = 2.33$, $z_{0.02} = 1.96$, $z_{0.05} = 1.645$

The release volume is then constrained to not exceed the specified refill probability/quantile, as in

Equation **8**.

Equation 8. Uncertainty-based Release Constraint:

$$\text{Release} = \max\left(Q_{out} = V_\alpha/(t_{peak} - t_{current}),\ Q_{out} = V_\alpha/(t_{event} - t_{current})\right)$$

Currently, the historical data is insufficient to determine whether uncertainty decreases with forecasted flow, remains constant, or increases. For simplicity, the standard deviation of the ratio of forecast to actual flow was assumed to be 0.3 and was assumed to remain constant. In the future this parameter could vary with flow, which would widen or narrow the quantiles, and would allow operations to reflect changes in uncertainty. USACE (USACE 2002) determined that little additional drawdown was achieved for refill probabilities below 90%, so refill probabilities estimated at 95%, 98%, and 99% were considered.

Another method that could be used to account for the uncertainty would be to include adjustable safety factors in the release computation, as in Equation 9. If volume safety factor e_v - or time safety factor e_t increase, the release would be smaller and less responsive to forecast information (and therefore less likely to make an unnecessarily large release). The volume factor and time factor could be based on the average magnitude error and average timing error of the historical forecasts.

Equation 9. Release Computation Using Safety Factors

$$Release = \max(Q_{out,p}, Q_{out,e})$$

Where $Q_{out,p} = (V_{peak} - V_{avail} - e_v)/(t_{peak} - t_{current} + e_t)$, and

$$Q_{out,e} = (V_{event} - V_{avail} + e_v)/(t_{event} - t_{current} - e_t))$$

A release computation using adjustable safety factors was not simulated in this thesis, but should be explored in future studies.

5.4. Relative Rule Priority

Finally, the release rule must be assigned a priority relative to other rules. If a large event does occur but is not forecasted, normal operations would lead to flood consequences such as certain channel damage, reduced warning times, and loss of life and structures. Although no benefits would be gained from forecast operations in this scenario, the addition of forecast rules to the existing models must not hinder the existing operating rules. Operations with forecasts must not result in more severe flood consequences than operations without forecasts.

To protect the dam and prevent sudden decreases in the release during large events, the rules from the emergency spillway release diagram (ESRD) must be higher priority than the forecast-based rules. Rate-of-change limits must also be assigned a higher priority to dampen steep spikes and drops in releases. To avoid flooding downstream, releases greater than the 160,000 cfs channel capacity must be delayed as long as possible. Lastly, releases greater than 115,000 can only be made if actual inflow exceeds 160,000 cfs.

During the flood, the emergency release is the highest priority. If necessary, releases above 160,000 cfs (channel capacity) will still be prescribed by the ESRD. By implementing the forecast-based rule at a lower priority than the ESRD and rate of change rules, the forecast-based releases are constrained while still allowing operations to react to changing information.

5.5. Other Rules Considered

USACE is considering forecast-base release rules from other groups including SAFCA and BOR. The rule proposed by BOR is similar to the Shasta release schedule discussed in the literature review; the rule proposed by MBK for SAFCA is more similar to the modified HEC rule. Since the BOR has not yet formulated or suggested appropriate thresholds for their release schedule, only the MBK rule is evaluated in this study. Rules based on the MBK formulation are referred to as the "MBK rule" (in contrast to the variations on the HEC formulation, or "modified HEC rule").

5.5.1. MBK Rule

The preliminary study prepared for SAFCA (MBK, 2012) adjusted the existing rules in the base ResSim model to include perfect lookahead, up to 48 hours, with a volume-based release computation. MBK's proposed formulation: (1) modifies the existing accelerated transition rule, setting a minimum release increment to prevent the forecast inflow from exceeding flood pool capacity, (2) modifies the smoothing routine with a minimum release increment to prevent forecast inflow from exceeding forecast guide curve, and (3) modifies the Fish and Wildlife service rule so that if peak forecasted inflow exceeds 150,000 cfs, the Fish and Wildlife limitations may be neglected in favor of larger releases. For comparison with other rules in this study, the formulation proposed by MBK was generalized to incorporate summaries of peak volume and peak flow from 72-, 48, and 24-hour *artificial forecasts*—rather than the perfect lookahead simulated in the preliminary study. The rule algorithms are summarized in Equation 10 through Equation 12.

Equation 10 Smoothing Routine:

$Q_{out,current}$ = min{115, 130, 145, 160 kcfs} such that $Q_{out} >= (V_{forecastlength}-V_{avail})/(\text{Forecast Length})$

where $V_{avail} = TOC_{forecast} - Storage_{current}$

Equation 11 Accelerated Transition:

$Q_{out,current}$ = min{115, 130, 145, 160 kcfs} such that $Q_{out} >= (V_{peak}-V_{avail})/(\text{Forecast Length})$

where $V_{avail} = TOF - Storage_{current}$

Equation 12 Fish and Wildlife:

If Q_{in} <150000 and El < 466 and $Q_{in,forecasted}$ <=150000:
$Q_{out,current} < \max(0.5*Q_{in,previous}, 0.6*Q_{in,forecasted,12hr}, Q_{out,previous})$

MBK's modified accelerated transition rule, which evaluates storage relative to the top of the flood pool, seeks to fill the flood pool. MBK's modified smoothing routine evaluates storage relative to the top of the Conservation Pool and thus seeks to empty the flood pool; the two rules have conflicting objectives. MBK's modified smoothing routine applies to releases between 0 and 115,000 cfs; the accelerated transition rule applies to releases between 115,000 cfs and 160,000. Between 0 and 115,000 cfs the objective of the releases is thus to keep storage as low as possible to prevent early filling of the reservoir. Between 115,000 cfs and 160,000 the objective of releases is to fill the reservoir, which helps attenuate peak flows and reduces the strain on downstream levees.

The MBK formulation has many similarities to the modified HEC formulation, and many subtle differences. Release ranges, rule objectives, and computation methods are a few of these key differences. Table 4 provides an at-a-glance comparison between MBK and modified HEC rules.

Table 4. Summary Comparison of MBK and Modified HEC formulations.

Name	MBK Rule		Modified HEC Rule
	Smoothing (modified)	Accelerated Transition (modified)	
Relation to Existing Rules	Modifies and Replaces Existing Smoothing Rule	Modifies and Replaces Existing Accelerated Transition	Higher priority than existing Accelerated Transition and smoothing rule
Trigger	Forecasted pool > top of conservation pool	Forecasted pool > top of flood pool	ForecastVolume > 1,000,000 acre –feet or forecast flow > 300,000 cfs
Release Range:	0 to 115,000 cfs (discrete-increments of 15,000 cfs)	115,000 to 160,000 cfs (discrete-increments of 15,000 cfs)	0 to 115,000 cfs when $Q_{in,\ current}$ < 160,000 cfs. 115,000 to160,000 cfs when $Q_{in,current}$ >160,000 (continuous)
Reference Elevation	TOC	TOF	TOF
Computation	Iterative,	Iterative	Direct
Objective	Evacuates flood pool when flood threat is not imminent	Maximizes storage in flood pool for minimum overflow.	Maximizes storage in flood pool for minimum overflow.
Considers forecast Uncertainty?	No	No	Yes

Since it is computed from the top of the flood pool, the MBK rule's accelerated transition component operates with a similar algorithm to the 99% rule; however, the smoothing routine component of the MBK release computation has a slightly different objective than the proposed 99% rule. Rather than computing space available relative to the top of the flood pool and filling the flood pool without overflow, the smoothing routine evaluates encroachment relative to the top of conservation pool (TOC) and evacuates encroached water from the flood pool. However, the smoothing routine component of MBK's rule is at a lower priority--near the bottom of each zone—allowing the higher priority accelerated transition component to prescribe full use of the flood pool.

Another notable difference between the MBK rule and the 99% rule is that the MBK rule computes releases iteratively. Rather than directly computing a release with the given information, releases are evaluated in increments of 15,000 cfs to determine the lowest release that draws down the forecast storage levels below top of conservation and top of flood. For the simulation of entire events, the iterative process is slower than the 99% method's direct computation, although this would not be noticeable in real-time operations. In addition, increments as large as 15,000 cfs may also lead to higher-than-necessary releases. For example, if the accelerated transition criteria in the MBK rule specify a minimum of 132,000 cfs, the lowest increment that would meet these criteria is 145,000 cfs--resulting in a release that is too high by 13,000 cfs. However, in real-time operations, increments of 15,000 cfs would be more practical for reservoir operators.

6. Tradeoffs and Comparison Methods

As discussed earlier, reservoir operation in general and the use of forecasts in particular are not without risks and tradeoffs. Unnecessary drafting of the pool could lead to severe consequences downstream such as increased strain on levees from prolonged flows, impacts to water quality and the cold water pool, water supply impacts from water released that is not recovered, hydropower energy spill, and unnecessary impacts to sensitive aquatic species and habitats. If channel capacity were exceeded due to forecast error, unnecessary loss of life and damage to structures could occur, and for this reason USACE policy is to prevent unnecessary forecast-based releases above channel capacity to the maximum extent possible. However, without the use of forecasts there remain considerable risks to downstream life, safety, and infrastructure.

Assumptions and simplifications which have been made to compare the performance of the rules are discussed in the following sections. A full sample calculation of rule performance appears in Appendix C.

6.1. Downstream Impacts and Probability of Levee Failure

The primary objective of the reoperation study and the Joint Federal Project is to protect downstream infrastructure by passing a 200 year-flood event volume with outflows of less than 160,000 cfs. The effectiveness of the forecast-based rule depends heavily on whether downstream levees are strengthened to withstand flows of 160,000 cfs. Advance release, and increasing forecast lead-time, nearly always decreases the length of time above 160,000 at the expense of prolonging the length of time above 115,000. The volume of water released is the same, but to flatten the hydrograph, the hydrograph must be stretched in time. This is a form of hedging; although individual simulations may appear to show no benefit, the overall likelihood of flows above 160,000 is reduced.

To quantify the net performance with these tradeoffs, the simulated flows and durations were applied to a geotechnical fragility curve with strengthened downstream levees and a geotechnical fragility curve without strengthened downstream levees. Geotechnical fragility curves describe the probability of levee failure with increasing water stages on the levee. USACE is developing stage-flow curves and stage-fragility curves for ongoing damage assessment models on the Lower American River to evaluate the approximate levee performance with expected structural improvements and with JFP operations. A stage-flow relationship and a stage-fragility relationship—both within the range of the USACE curves under development—were selected to represent a generic reach. The stage-flow and stage-fragility relationship for the generic reach were then combined and interpolated to determine an approximate probability of failure for flows between 115 and 160 kcfs (Figure 10). At flows above 160,000 the levees overtop and the failure probability is assumed to be 100%.

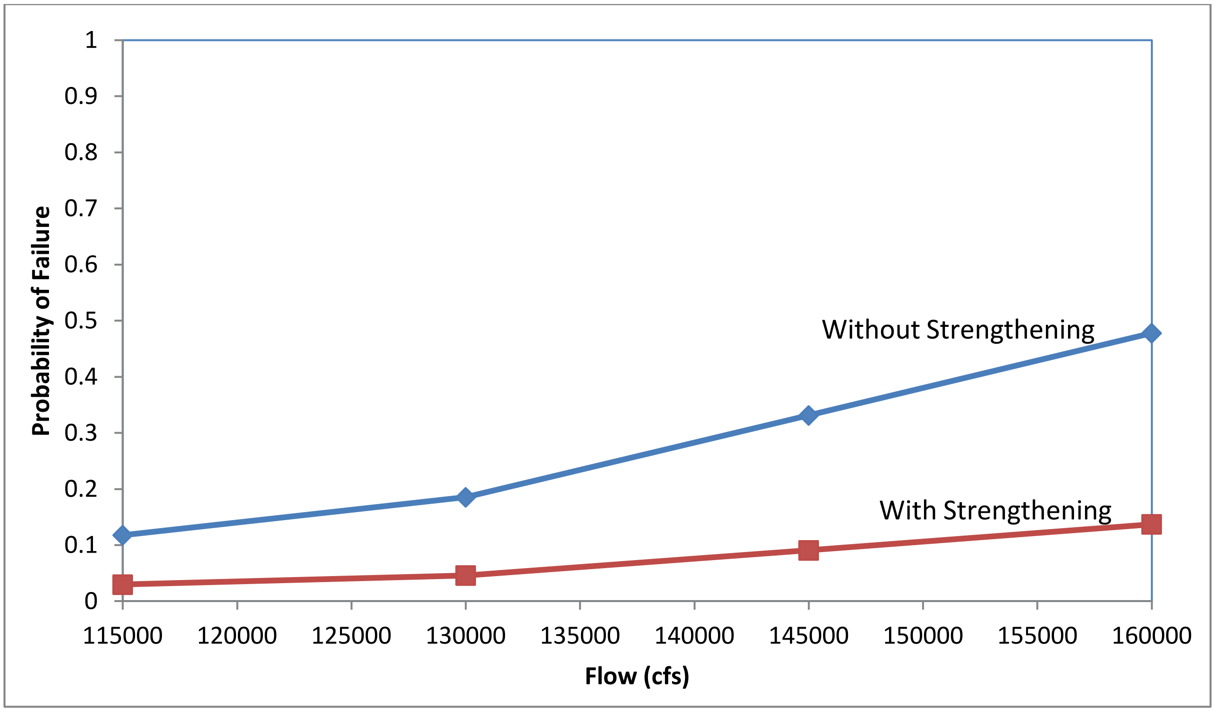

Figure 10. Generic Outflow vs. Probability of Failure Curves for Downstream Levees

The analysis thus far considers only the magnitude of the flows, not the duration. However, many of the failure modes are duration-dependent in addition to being flow-dependent. Typical USACE geotechnical fragility curves include the following failure modes: through-seepage, under-seepage, rodents, utilities, vegetation, and erosion. Through-seepage and underseepage begin at flows of 115,000 cfs or greater; erosion also increases substantially above 115,000 cfs due to the increased velocity (Ayres, 1997).

Attempts to quantify the critical duration for erosion at 115,000 cfs and 160,000 cfs on the American River levees are ongoing, and USACE has not issued a conclusive determination of how long levees can withstand these high flows. Reports indicate that the levees almost failed in 1986 after 2.5 days of flow above 115,000 cfs; however, the levees withstood that event and the 1997 event (Ayres, 1997) and critical segments have since been repaired and strengthened. Approximate times to failure are therefore estimated to range between 30 days and 3 days for flows between 115,000 and 160,000 cfs; failure is assumed to be immediate when flows exceed 160,000 and the levee is overtopped. Assumed times to failure for each outflow are shown in Table 5.

Table 5. Hours to Failure at Each Outflow for the Specified Failure Probability.

Outflow (cfs)	Failure Probability ($P_{f,i}$)	Hrs to Failure ($T_{Fail,i}$)
<=115000	0	--
115000	0.263	720
130000	0.297	360
145000	0.331	180
160000	0.366	72
>160000	1	0

To include the duration in the evaluation of levee performance, the failure probabilities were then scaled linearly upward or downward if the simulated duration was longer or shorter than the estimated average time to failure for erosion. The probability of failure was then calculated as below, in Equation 13—a very simplified representation of a much more complex probability calculation. A sample calculation for one rule appears in Appendix C.

Equation 13. Failure Probability

$$P(f) = \sum_{i=115000}^{16000} \frac{P_{f,i} * (T_{Q>i+1} - T_{Q>i})}{T_{Fail,i}}$$

where $T_{Q>i}$ is the simulated duration of flows above a certain flow i,

$P_{f,i}$ is the probability of failure at or above a certain flow,

and $T_{Fail,i}$ is the average time which it takes to erode the levee at flow i.

A previous estimate of the probability of downstream levee failure for a 200-year flow without forecast operations was 83% (USACE 2001). Using Equation 13 described above, the probability of downstream levee failure without forecasts was estimated at 70%. The difference between the estimates can be due to different fragility curves, different operational rules, or a number of different simplifying assumptions.

Many simplifications were made to estimate the probabilities of downstream levee failure. One generic index point was selected to represent an entire downstream system of levees, and curves for stage-flow and stage-failure probability were estimated at discrete points. Hours to failure were also estimated, based on limited historical information and professional judgment. Since erosion begins with flows slowly eroding away vegetation, then more rapidly eroding the fine grained soils, erosion is a nonlinear process. The failure probabilities may not scale linearly up or down with duration relative to the estimated hours to failure. Further, the hours to failure are likely higher for some modes of failure than others—it may take longer for a levee to fail due to rodent burrows than due to erosion, for example. Curves for stage-flow and stage-failure probability are subject to error as well. Finally, the summation process used rough increments of 15,000 cfs—only four points, including interpolated points. Nevertheless, rough estimates had to be made to compare the rules. When the geotechnical performance of the American River levees is better quantified, and when the fragility analyses include durations in addition to stages, the rules can be better ranked or optimized.

6.2. Weighting of Shapes

To combine the probabilities of failure for different shapes into one probability of failure describing the rule, a weighted average had to be computed.

As discussed in Section 3.3, the 6 hydrographs studied were based upon preliminary scaling factors which attempted to approximate a 200-year return period assuming a 3-day critical duration. According to more recent estimates from USACE, the return periods for the 6 hydrographs are in general higher than 200 years when computed with the 3-day duration, and vary between 130 and 250 years.

Nevertheless, as an illustrative example, the shapes were weighted according to their relative preliminary scaling factors. Since some hydrograph shapes were scaled more than others to obtain the preliminary 200-year 3-day volume, the results from routing the shapes could not be simply averaged. Operations based on 1955 shapes and 1964 shapes were given less weight than the 1986 and 1997 shapes because the actual floods of 1986 and 1997 were closer to the hypothetical 200-year flood. Weights were determined as the percentage of the sum of the inverses of the scaling factors.

The Central Valley Hydrology Study (CVHS) also specified weights for 1955, 1964, 1986, and 1997. This weighting scheme—adjusted to add the PMF and SPF floods—was considered as well. Table 6 shows the preliminary scaling factors used for each shape and the relative weights assigned to each.

Table 6. Relative Weights for each Hydrograph Shape

	Return Period	Preliminary Scaling Factor	1/Scaling Factor	Weight	CVHS Weight	Final
PMF	***	1.0875	0.92	0.21	--	0.1
SPF	240	1.0199	0.98	0.22	--	0.1
1955	130	1.6182	0.62	0.14	0.167	0.1336
1964	240	1.8172	0.55	0.13	0.178	0.1424
1986	220	1.4814	0.68	0.15	0.298	0.2384
1997	250	1.5814	0.63	0.14	0.359	0.2872

The method using scaling factors to determine weight was problematic for the PMF and SPF shapes. Although they were artificial, the PMF and SPF shapes were weighted the highest. The true hydrographs which they were based on may have been less probable than the weights suggest. The CVHS weights are inconsistent due to the varying scaling factors, but reflect more reasonable weightings for the PMF and SPF shapes. Therefore, the adjusted CVHS weighting scheme was selected. The use of the weights to determine an average failure probability is illustrated in Appendix C.

Although the weighting scheme will suffice for the present illustrative exercise, future studies should evaluate the 6 shapes scaled to the same estimated return period, and scaling factors should be updated to represent the final results of the critical duration analysis for the 200-year return period.

6.3. Water Supply Impacts

Since the proposed rules are not configured to release water from the conservation pool, water supply impacts—if any—will be limited. Water supply can only be affected if the following two conditions are met: (1) a flood must be forecasted which does not materialize in the flood pool, and (2) the reservoir would have ended the month significantly encroached in the flood pool under operations without forecasts. This is the only case in which more water could be released than strictly necessary--if the large forecasted event does not actually materialize and prereleases were made, but the flood pool would have returned to guide curve by the end of the month anyway, the forecast release does not have an effect on water supply.

As discussed in Section 4 of this study, the rate of false alarms is unknown and a subject of further study with hindcasts. However, the second criteria, flood pool encroachment, can provide an upper bound to the probability of water supply impacts. Results from the base model period of record run show that the end-of month flood pool was encroached 310 times throughout the 671-month period of record: a 32% chance of ending the month with water stored in the flood pool (Figure 11). Points that fall below 0 ac-ft Storage Available on Figure 11 are encroached.

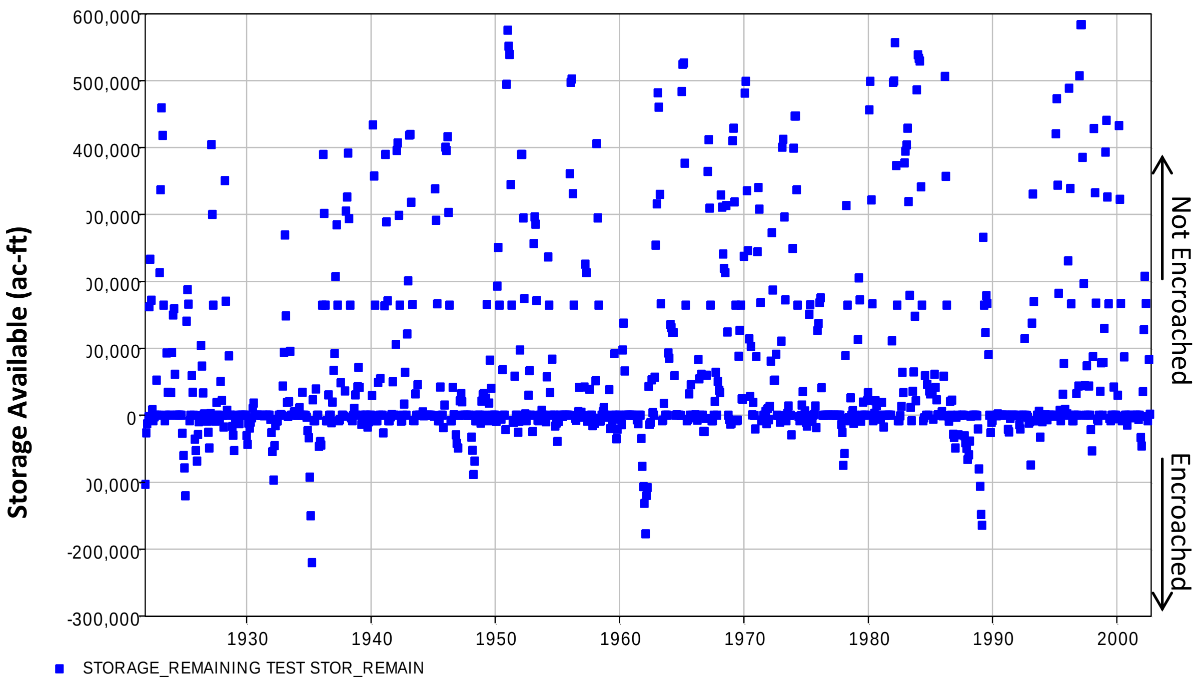

Figure 11. Months ending Encroached and not Encroached in POR

Most of the months which end with water stored in the flood pool are only encroached by 25,000 acre-feet or less; approximately 10 percent of months end with greater than 25,000 acre feet encroachment, and approximately 2 percent of months end with greater than 100,000 acre feet encroachment. This could perhaps be an indication of the current operational set's difficulty in drawing the reservoir back down to the guide curve after rain events lead to storage in the flood pool, or could be an issue with zone-boundary logic in ResSim itself.

Even if the month ends encroached due to the timing of the event, encroachments of 25,000 acre-feet or less would not last long and are not considered to be significant. The upper bound for the probability of water supply impacts would thus be approximately 10%, although the second criteria of false alarm would also have to be met. This second criteria would reduce the likelihood of impact even further. When the rate of false alarms is known, the constraint of releasing no more than is 99% likely to be recovered will limit the likelihood of releasing more than actually arrives at the reservoir to 1% of that 10%. For rules which do not incorporate uncertainty, the likelihood of unnecessary water supply impacts is estimated at 50% of that 10%.

6.4. Optimization

The optimal refill probability-and therefore the optimal release rule under the modified HEC formulation—would be calculated by minimizing the sum of flood and water supply costs, balancing the marginal expected cost of lost water supply and the marginal expected cost of flood damages if levees fail. Although attempts were made to quantify the levee failure probabilities and probabilities of water supply impacts for a range of cases, a full optimization is beyond the scope of this thesis. However, a function that could be used to optimize the refill probability based on water supply and flood damages is described in

Equation 14 and a conceptual schematic is presented in Figure 12.

Equation 14. Optimization Function

$$\text{Optimum Cost} = \text{Min}[\sum_{i=115000}^{16000} \frac{P_i|P_r * P_{f,i} * (T_{Q>i+1,Pr} - T_{Q>i,Pr}) * C_i}{T_{Fail,i}} + \sum_{j=0}^{200000}((1 - P_r) * P_{j,Pr} * C_j)]$$

Where:

P_r= refill probability (Variable to optimize)

$P_i|P_r$ = probability of flow *i* given operations with refill probability P_r, based on POR simulation,

$P_{f,i}$ = probability of failure at or above a certain flow *i*, given by the fragility curves,

$T_{Q>i,Pr}$ = Duration of flows above flow *i*, based on event simulation using refill probability P_r

$T_{Fail,i}$ = average time which it takes to erode the levee at flow *i*.

C_i = Cost of flood damages at flow *i*

$P_{j,Pr}$= Probability flood pool is encroached by volume *j*, based on POR simulation using refill probability P_r.

C_j = Cost of lost water supply volume *j*

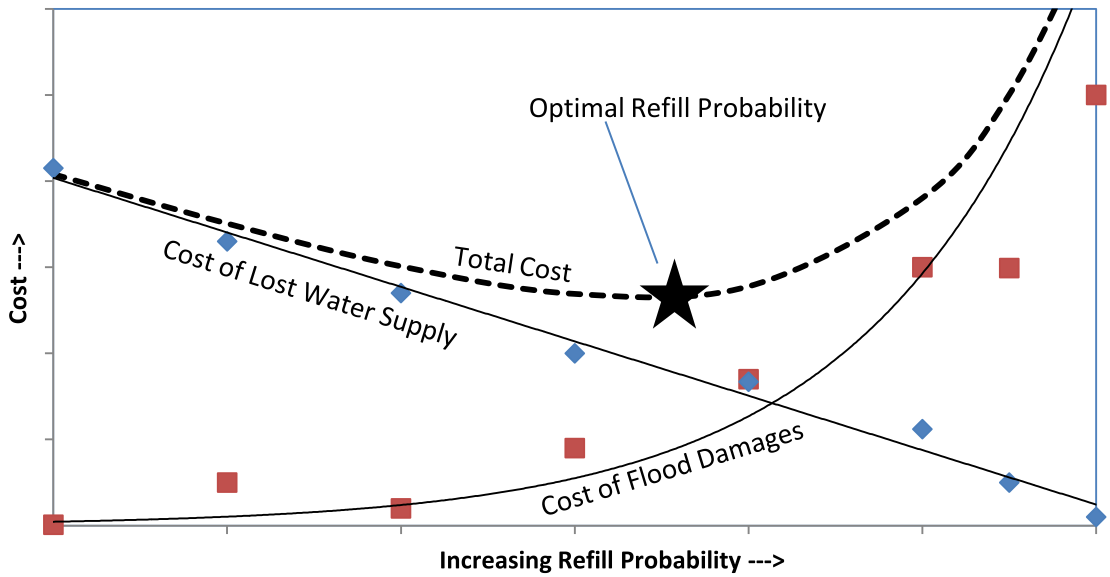

Figure 12. Schematic of Optimization for Refill Probability

Costs accounting for early unnecessary levee damage, spilled hydropower energy, and unnecessary fisheries damages have been neglected for this illustrative exercise, but could be incorporated into the optimization as well. The equation may also overestimate the expected cost of lost water supply, since it assumes that if the reservoir is encroached all of the encroached water would be lost.

7. Results

7.1. Start Trigger Sensitivity

The sensitivity of the operation to changes in the start trigger was assessed by simulating 6 cases starting at two different elevations and with three different start triggers. The reservoir was initialized at the lowest guide curve, 600 thousand acre-feet flood storage space with no upstream storage credit available; and at the highest (currently acceptable) guide curve, 400 thousand acre-feet flood storage space with empty upstream reservoirs and full storage credits. Only one set of imperfect artificial forecasts for each hydrograph was used (the "on-time" forecast, Appendix B). The outcome is shown for each 200-year-scaled event shape in Figure 13(a) through Figure 13(l), below.

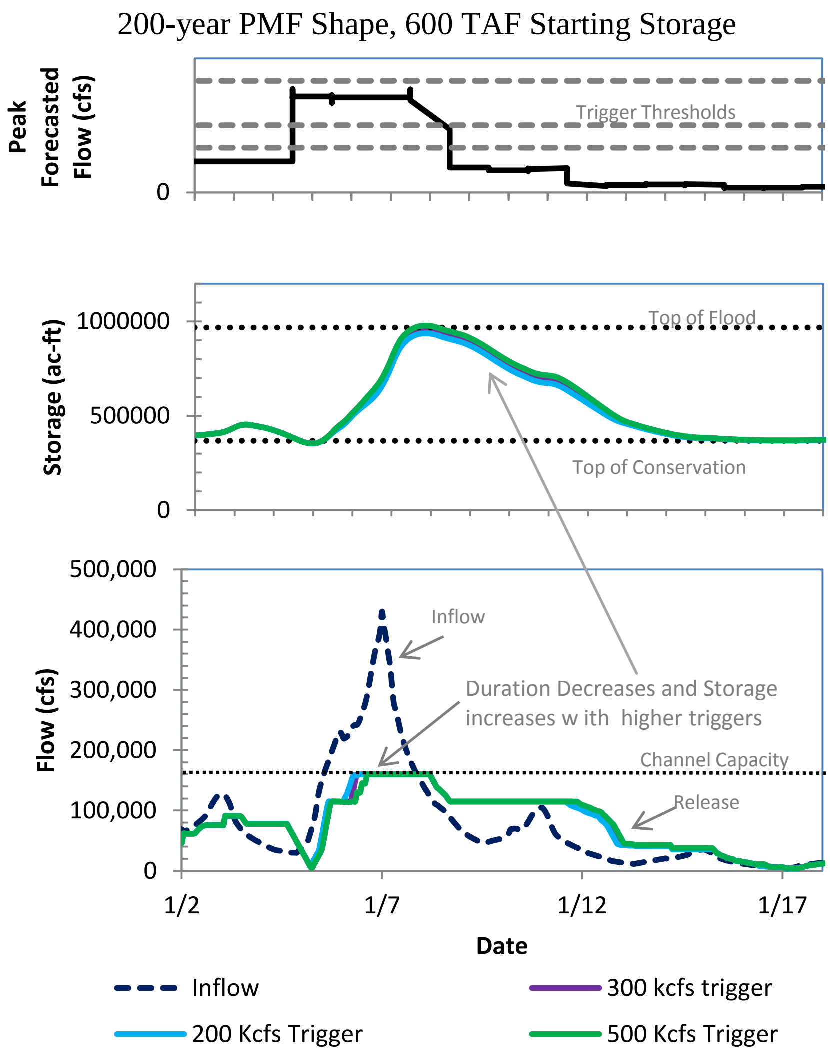

Figure 13(a)

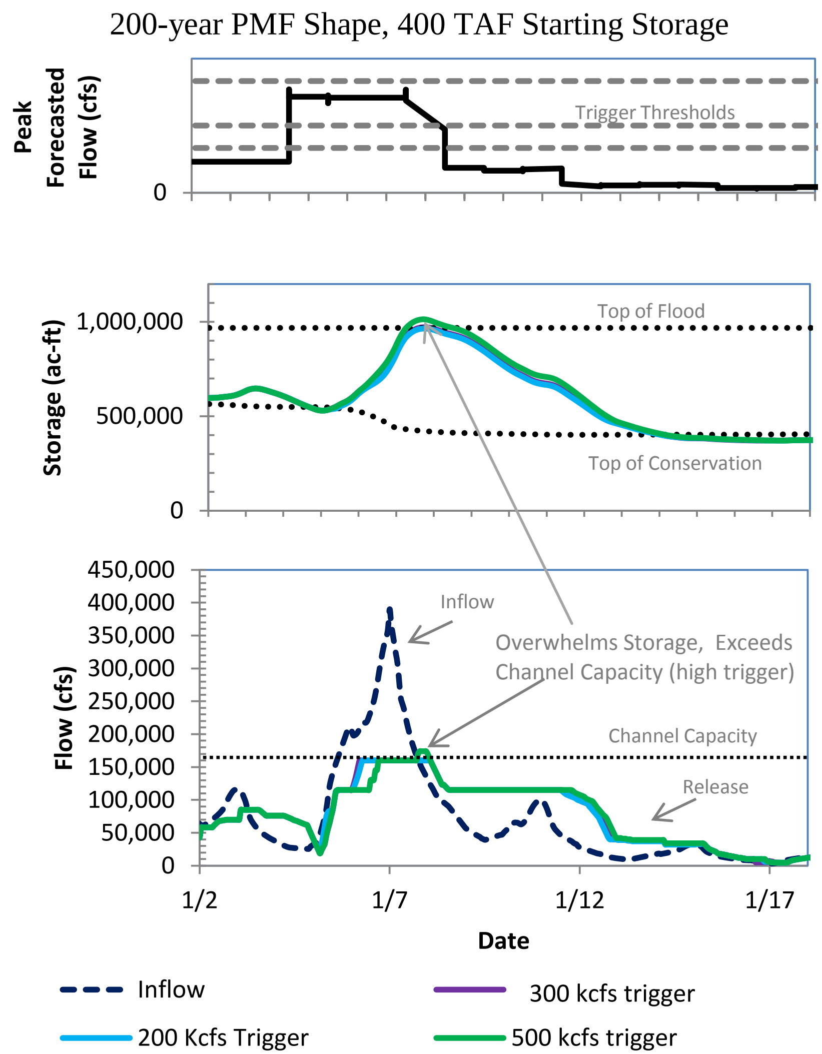

Figure 13 (b)

Figure 13. 1-in-200 year Operations for Various Flood Shapes, Sensitivity to Trigger

200-year SPF Shape, 600 TAF Starting Storage

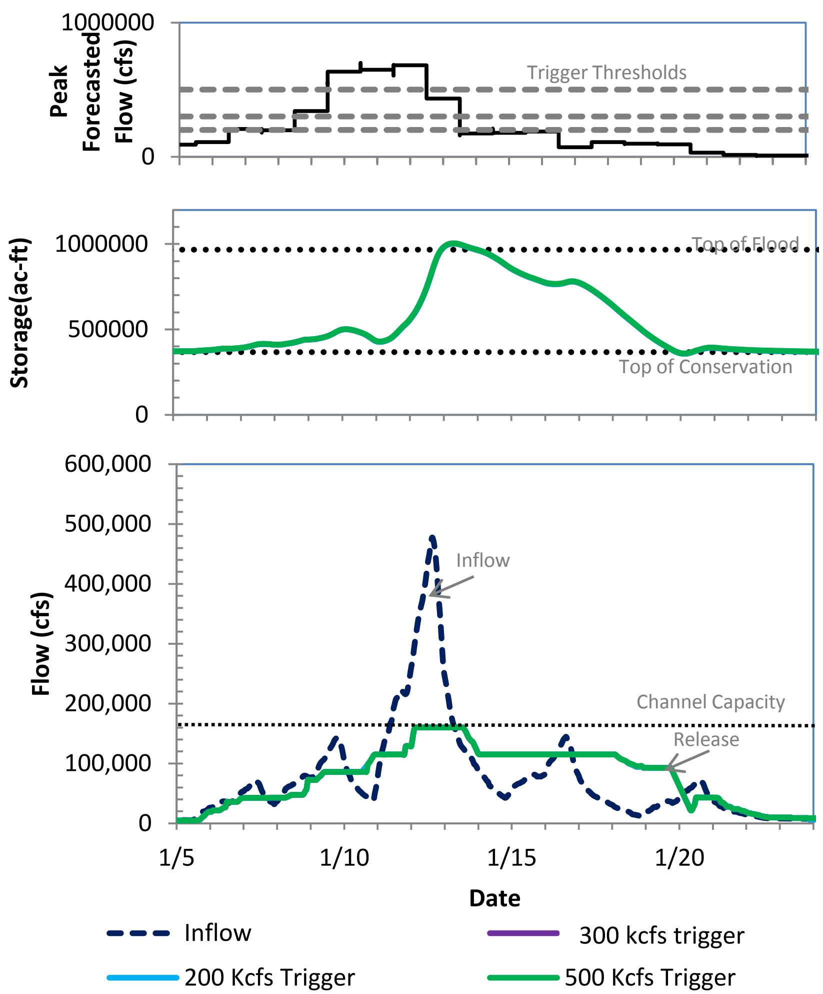

Figure 13 (c)

200-year SPF Shape, 400 TAF Starting Storage

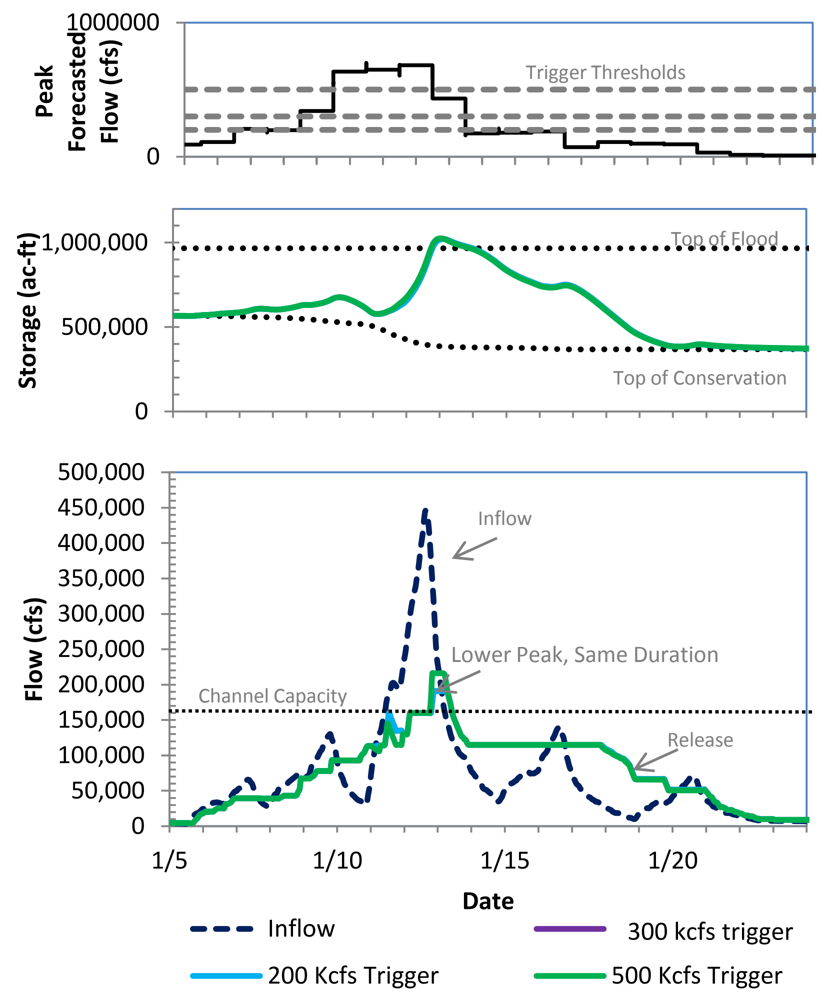

Figure 13 (d)

Figure 13**, continued.**

200-year 1955 Shape, 600 TAF Starting Storage

200-year 1955 Shape, 400 TAF Starting Storage

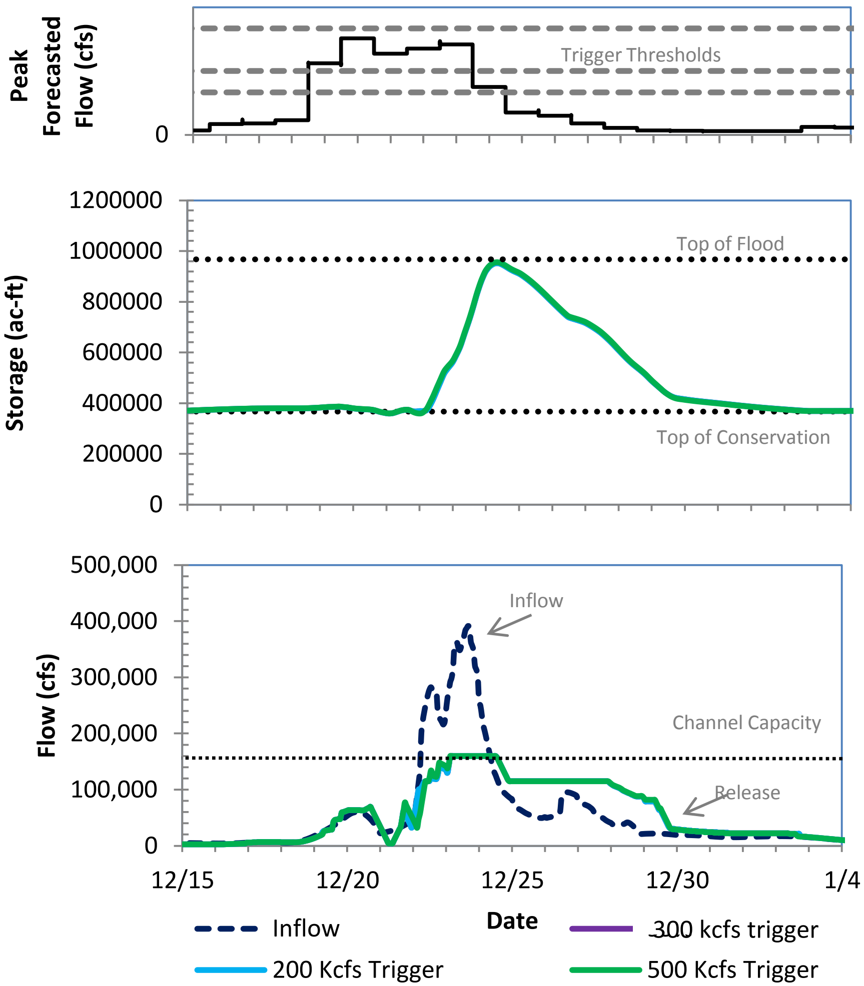

Figure 13 (e)

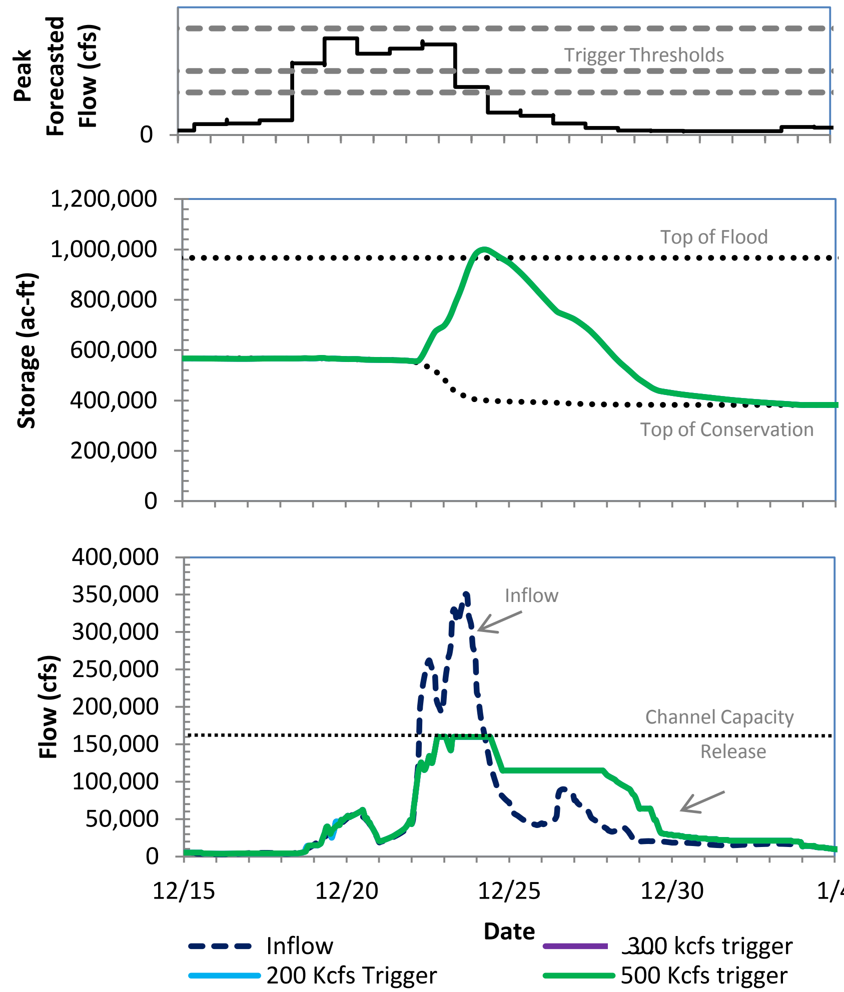

Figure 13 (f)

Figure 13, continued.

200-year 1964 Shape, 600 TAF Starting Storage

200-year 1964 Shape, 400 TAF Starting Storage

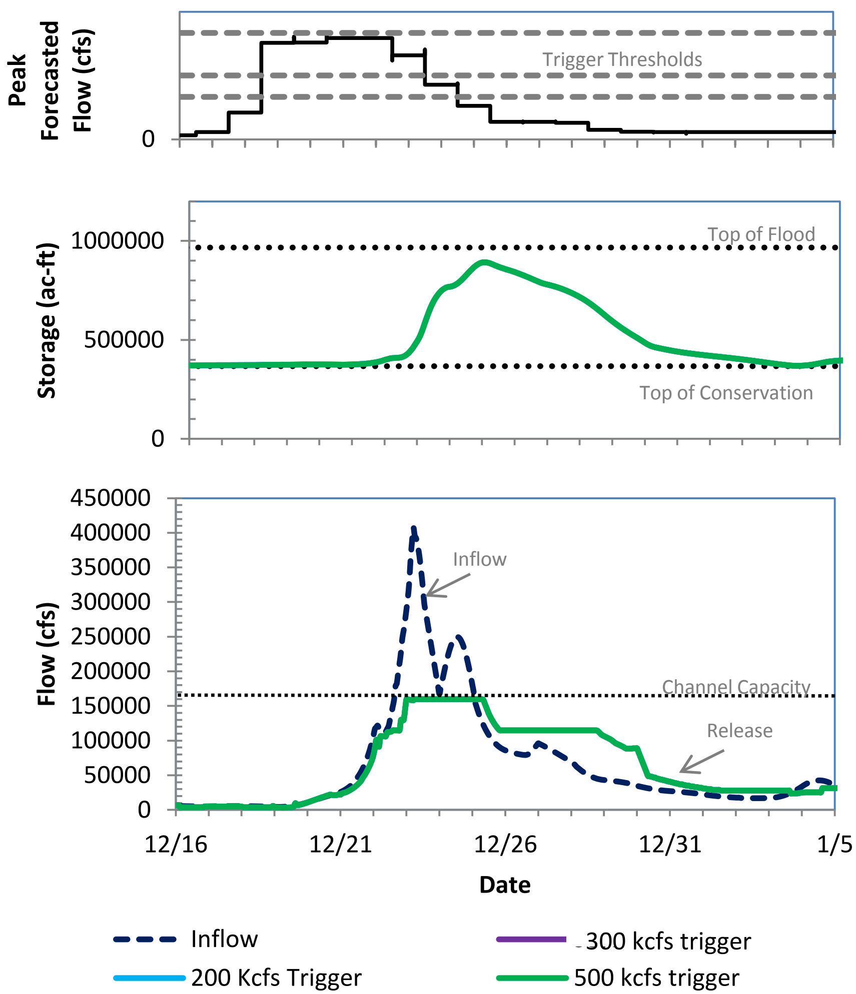

Figure 13 (g)

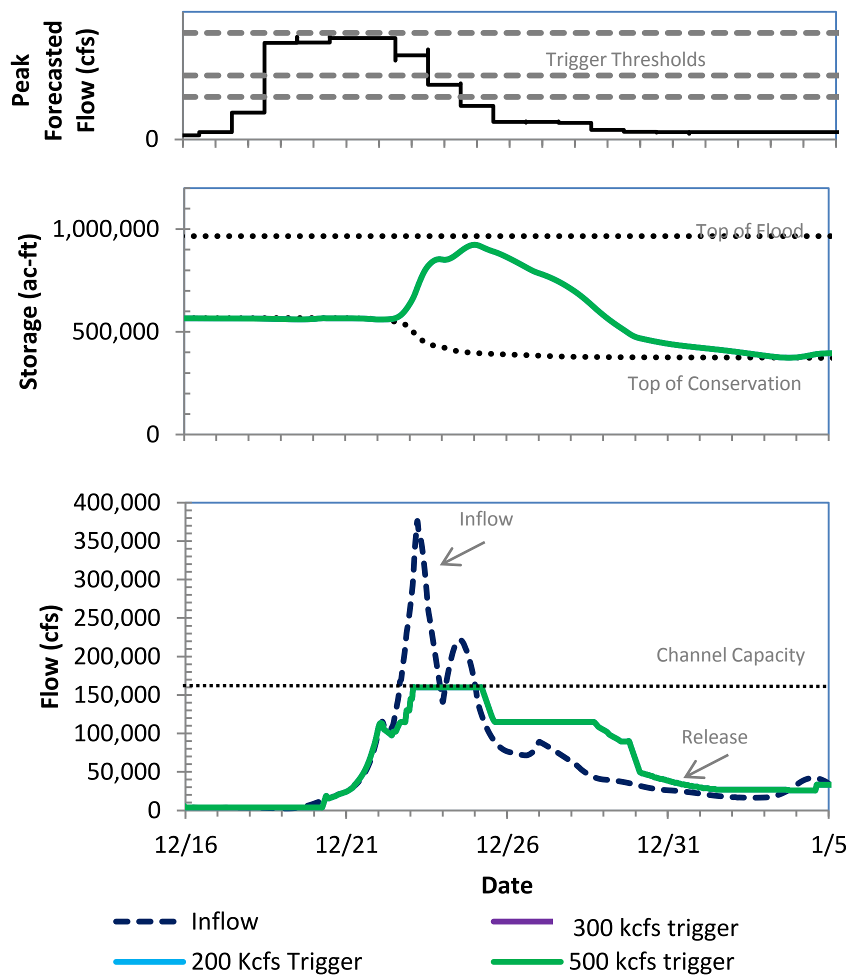

Figure 13 (h)

Figure 13, continued.

200-year 1986 Shape, 600 TAF Starting Storage

200-year 1986 Shape, 400 TAF Starting Storage

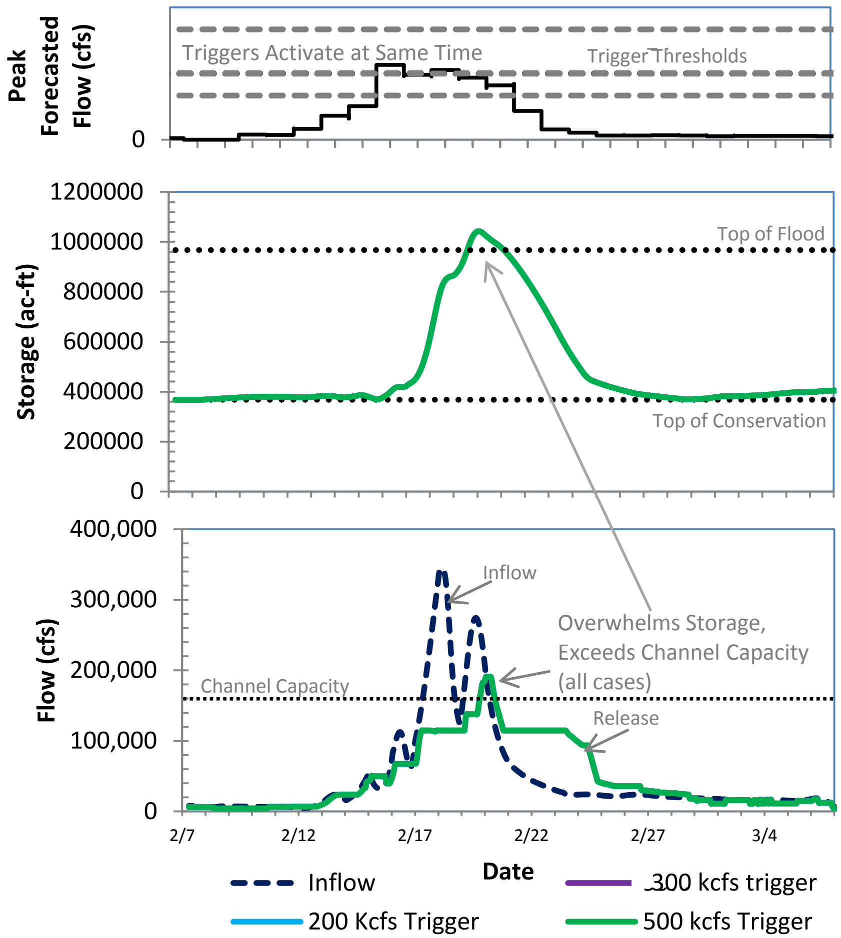

Figure 13(i)

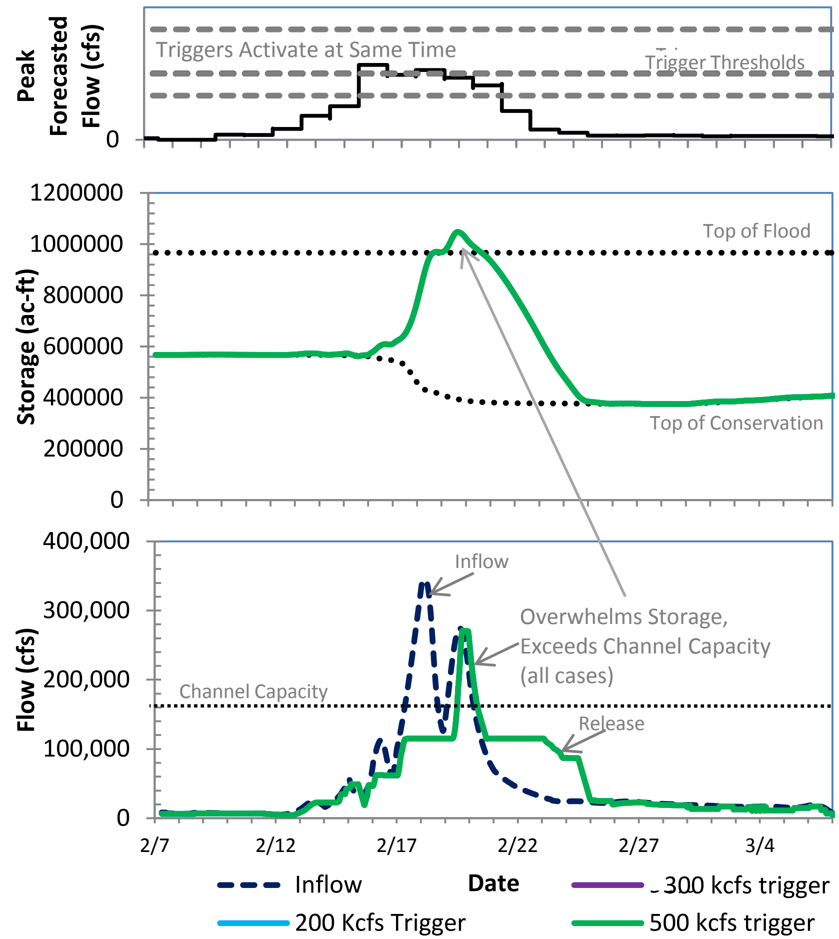

Figure 13 (j)

Figure 13**, Continued.**

200-year 1997 Shape, 600 TAF Starting Storage

200-year 1997 Shape, 400 TAF Starting Storage

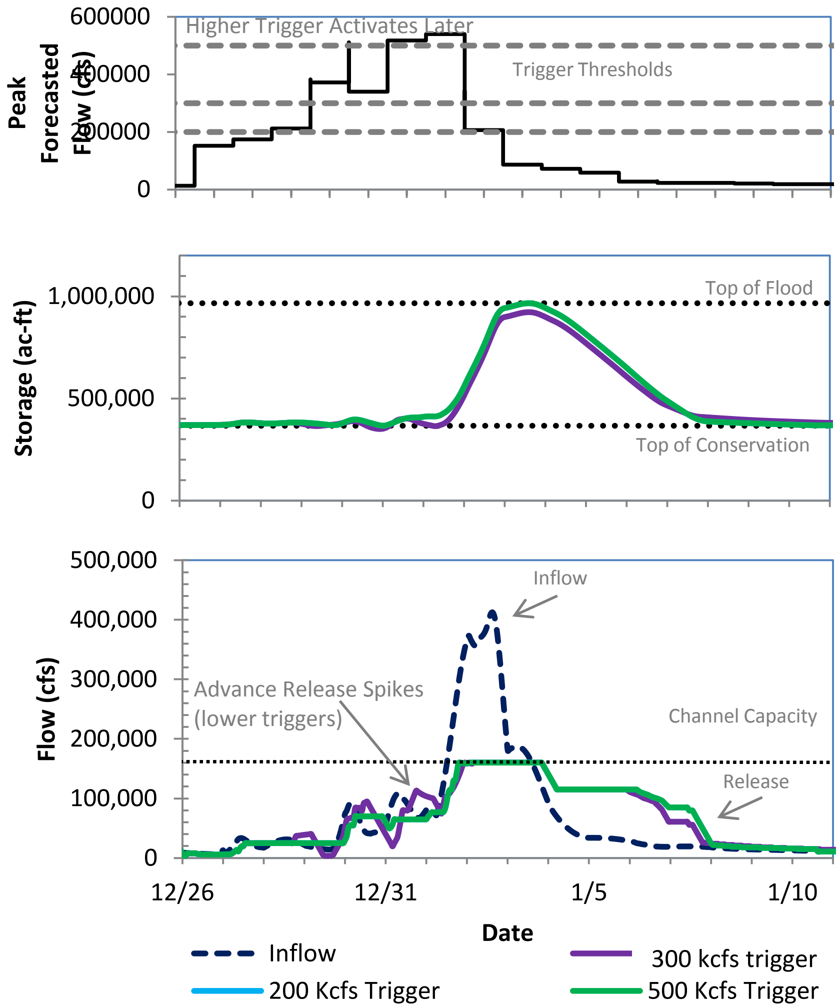

Figure 13 (k)

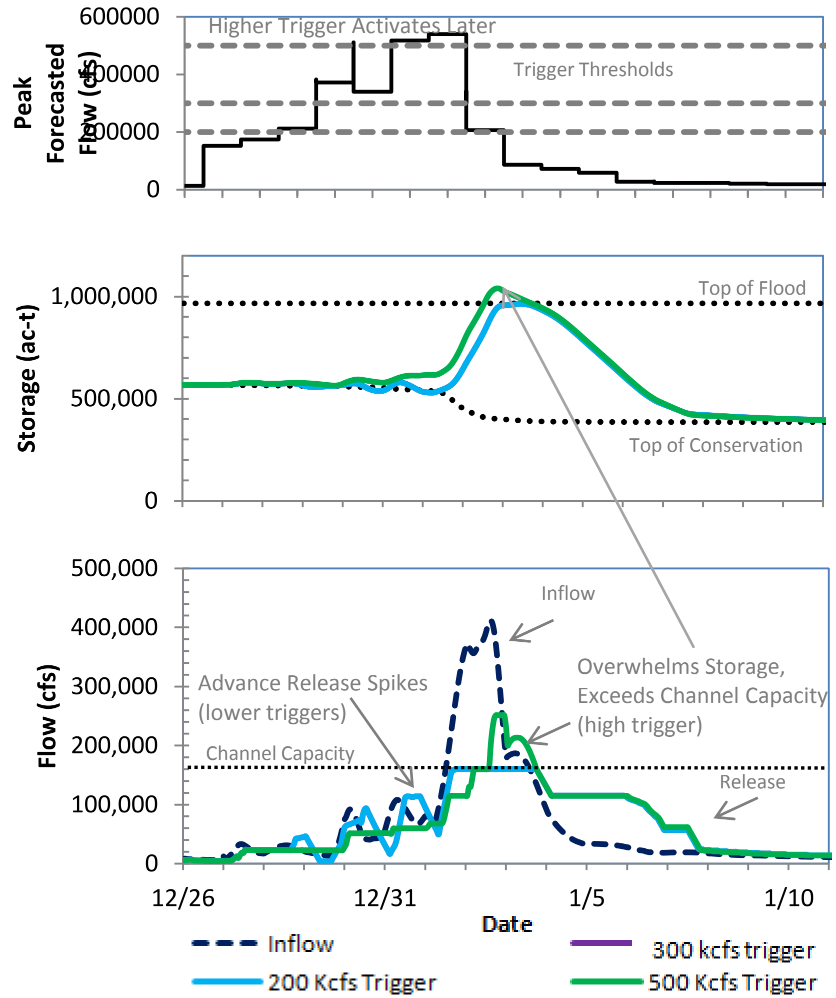

Figure 13 (l)

Figure 13, continued.

The results are outlined in Table 7a through Table 7f.

Table 7a Sensitivity to High vs. Low trigger (full upstream credit and no credit, each event)

PMF	600 TAF	600 TAF	600 TAF	400 TAF	400 TAF	400 TAF
Trigger (kcfs forecasted)	200	300	500	200	300	500
Peak Storage (TAF)	935.9	961.4	977.8	962.8	970.3	1013
Peak Outflow (kcfs)	160	160	160	160	160	**174**
Duration >115 kcfs (hr)	64	66	56	61	61	50
Duration >160 kcfs (hr)	0	0	0	0	0	8
Failure Probability	9%	9%	8%	8%	9%	100%

Table 7b

SPF	600 TAF	600 TAF	600 TAF	400 TAF	400 TAF	400 TAF
Trigger (kcfs forecasted)	200	300	500	200	300	500
Peak Storage (TAF)	1,003	1,003	1,005	1022	1,022	1,024
Peak Outflow (kcfs)	160	160	160	**191**	**191**	**216**
Duration >115 kcfs (hr)	53	53	53	59	59	54
Duration >160 kcfs (hr)	0	0	0	15	15	16
Failure Probability	7%	7%	7%	100%	100%	100%

Table 7c

1956	600 TAF	600 TAF	600 TAF	400 TAF	400 TAF	400 TAF
Trigger (kcfs forecasted)	200	300	500	200	300	500
Peak Storage (TAF)	952.3	952.3	956.5	999.4	999.4	999.4
Peak Outflow (kcfs)	160	160	160	160	160	160
Duration >115 kcfs (hr)	58	58	58	61	61	61
Duration >160 kcfs (hr)	0	0	0	0	0	0
Failure Probability	7%	7%	7%	7%	7%	7%

Table 7d

1964	600 TAF	600 TAF	600 TAF	400 TAF	400 TAF	400 TAF
Trigger (kcfs forecasted)	200	300	500	200	300	500
Peak Storage (TAF)	891.9	891.9	891.9	924.7	924.7	924.7
Peak Outflow (kcfs)	160	160	160	160	160	160
Duration >115 kcfs (hr)	72	72	72	66	66	66
Duration >160 kcfs (hr)	0	0	0	0	0	0
Failure Probability	10%	10%	10%	10%	10%	10%

Table 7e

1986	600 TAF	600 TAF	600 TAF	400 TAF	400 TAF	400 TAF
Trigger (kcfs forecasted)	200	300	500	200	300	500

Peak Storage (TAF)	1043	1,043	1,043	1047	1,047	1,047
Peak Outflow (kcfs)	**191**	**191**	**191**	**271**	**271**	**271**
Duration >115 kcfs (hr)	39	39	39	33	33	33
Duration >160 kcfs (hr)	16	16	16	21	21	21
Failure Probability	100%	100%	100%	100%	100%	100%

Table 7f

1997	600 TAF	600 TAF	600 TAF	400 TAF	400 TAF	400 TAF
Trigger (kcfs forecasted)	200	300	500	200	300	500
Peak Storage (TAF)	966.8	966.8	966.8	963.5	963.5	1,040
Peak Outflow (kcfs)	160	160	160	160	160	**251**
Duration >115 kcfs (hr)	61	61	61	62	62	49
Duration >160 kcfs (hr)	0	0	0	0	0	29
Failure Probability	9%	9%	9%	10%	10%	100%

The lowest trigger--which activated the rule when forecast inflow reached 200 kcfs--activated earlier than the other triggers for the PMF, SPF, and 1955 shapes. The low trigger activated at the same time as the other triggers for the other shapes. For both of the PMF shape cases, the 500 kcfs trigger did not activate the forecast rule; thus, the reservoir was allowed to store more water during the event, leading to outflows slightly higher than channel capacity when starting with 400 TAF flood space. For the 1997 shape and the SPF shape starting with 400 TAF flood space, the higher trigger did activate—but it activated too late, leading to higher overall releases. For all other shapes, however, the operations with the both the 500 and the 300 kcfs triggers reduced outflows to 160 kcfs.

Results for peak elevation and peak outflow were not sensitive to changes in the forecast trigger, perhaps due to the range of error in the forecast. In all cases, the peak-flow based trigger activated the rule sooner than the volume trigger, which was held constant for the rules; the volume trigger should be varied and sensitivity analyses should be conducted to determine an appropriate threshold for future rule implementation. To avoid unnecessary early use of forecasts while still providing timely response, the 300 kcfs peak flow trigger was chosen for further simulation—the proposed rule is active when forecast inflow reaches 300 kcfs and forecast inflow volume reaches 1,000,000 acre-feet.

7.2. Use of Conservation Pool

The conservation pool could provide additional flexibility in the case of a large flood. Advance release which evacuates water from the conservation pool is currently not supported; however, the idea was evaluated to determine whether it could provide additional benefit. Floods were simulated including forecast operations in the conservation zone, and without operations in the conservation zone. An imperfect artificial forecast, the “on-time” forecast (Appendix B), was used in the simulation. Results are plotted in Figure 14a through Figure 14l and tabulated in Table 8a and Table 8ab.

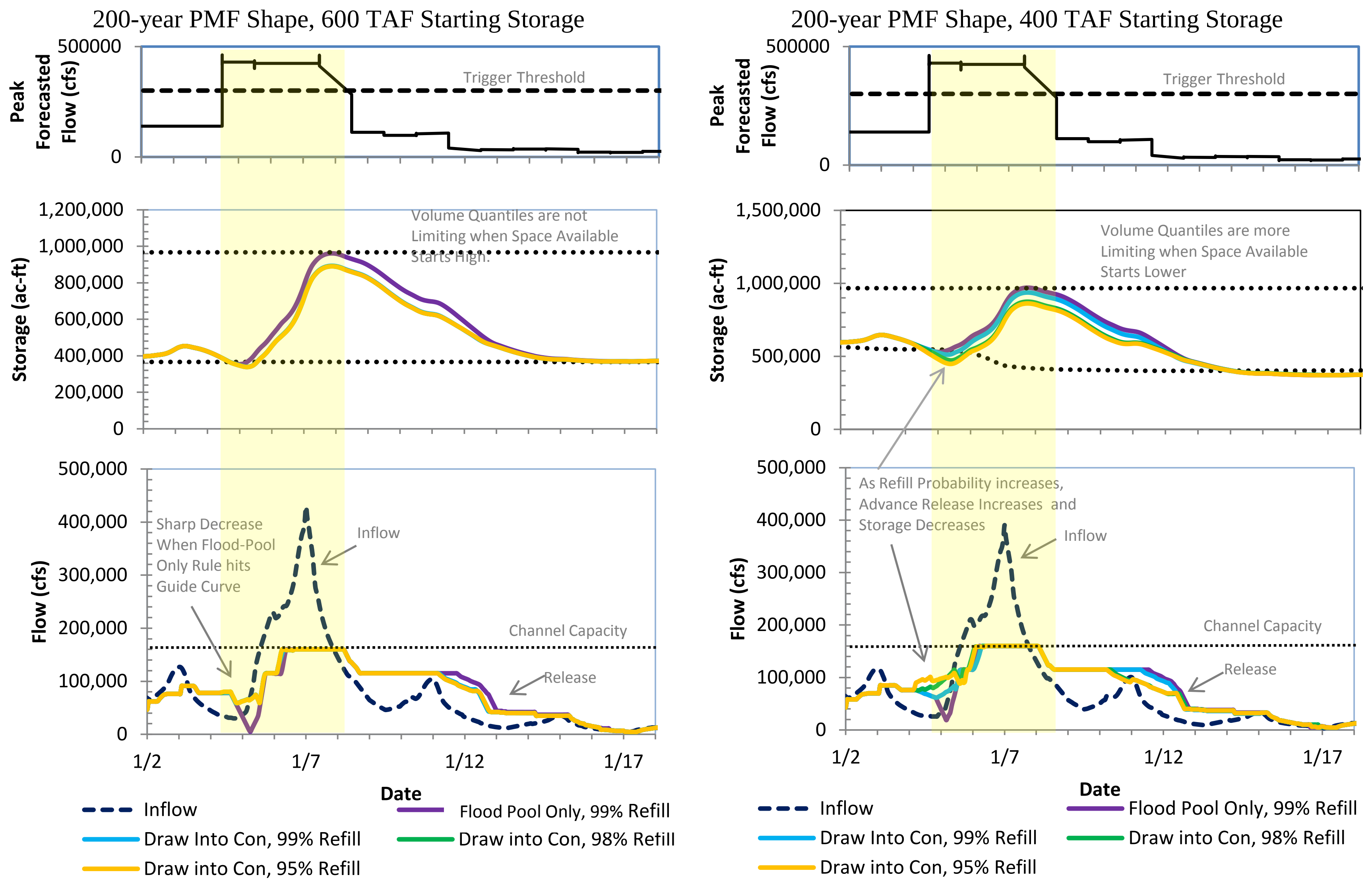

Figure 14(a) Figure 14(b)

Figure 14. Use of Conservation Pool for Advance Release

200-year SPF Shape, 600 TAF Starting Storage

200-year SPF Shape, 400 TAF Starting Storage

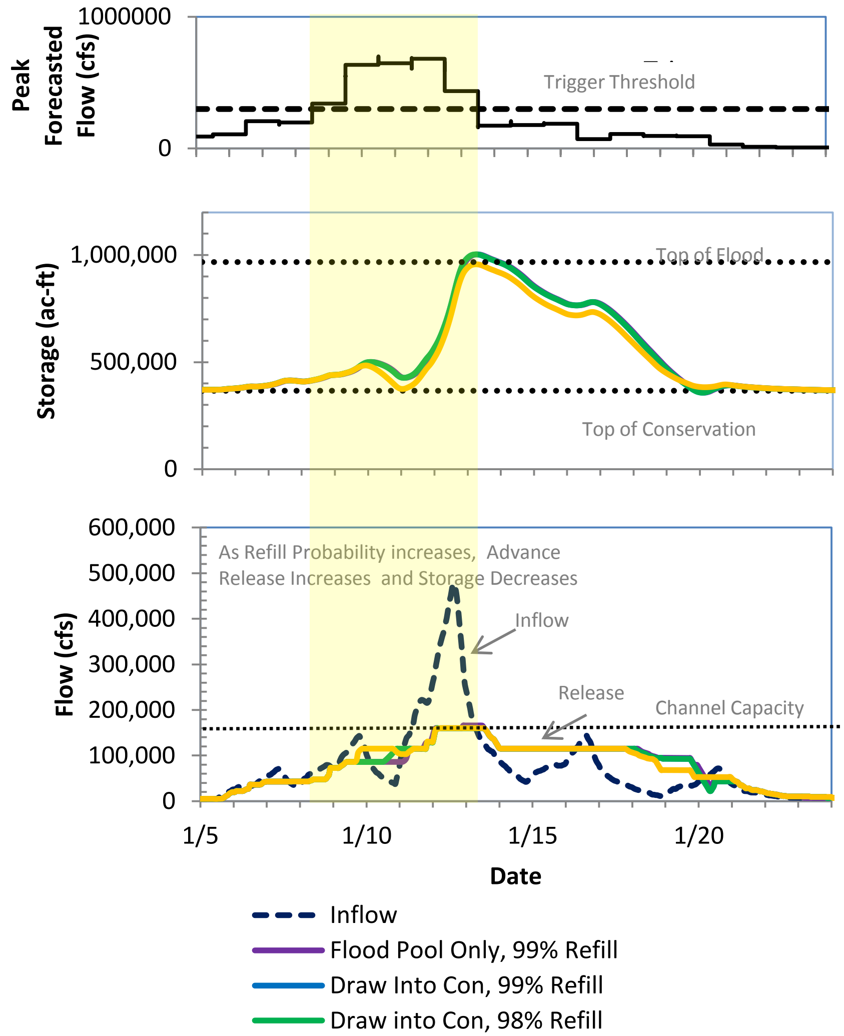

Figure 14(c)

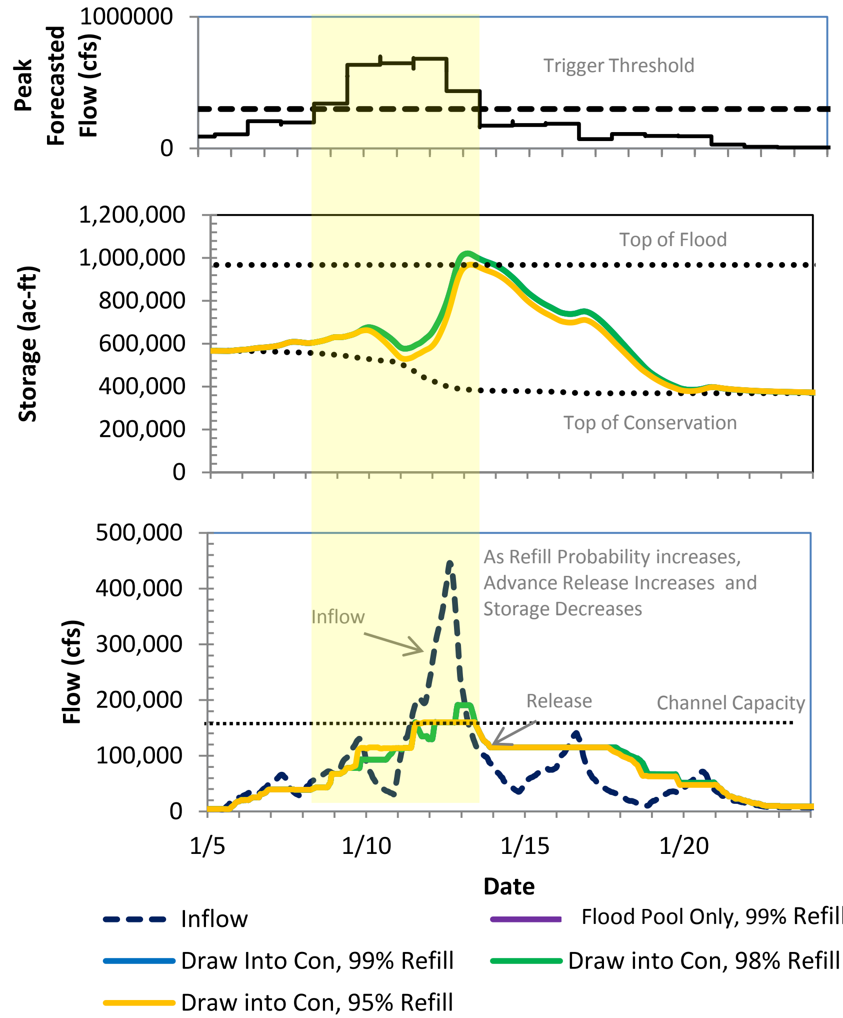

Figure 14 (d)

Figure 14, continued

200-year 1956 Shape, 600 TAF Starting Storage

200-year 1956 Shape, 400 TAF Starting Storage

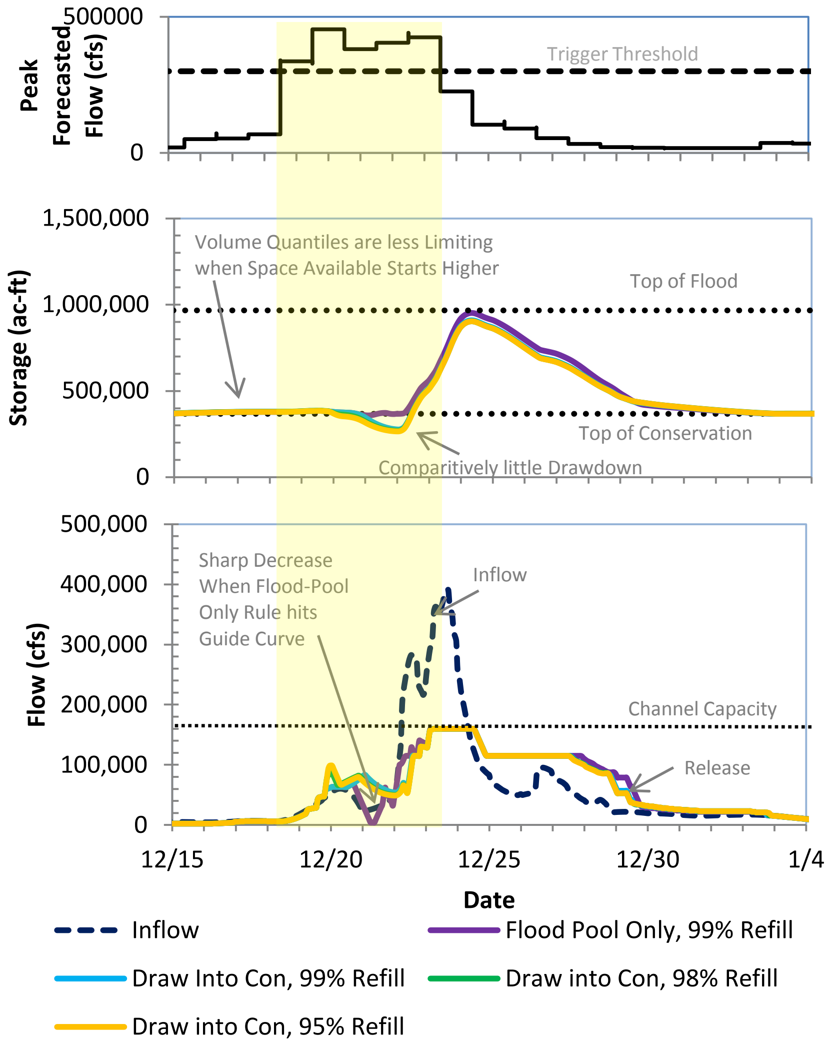

Figure 14(e)

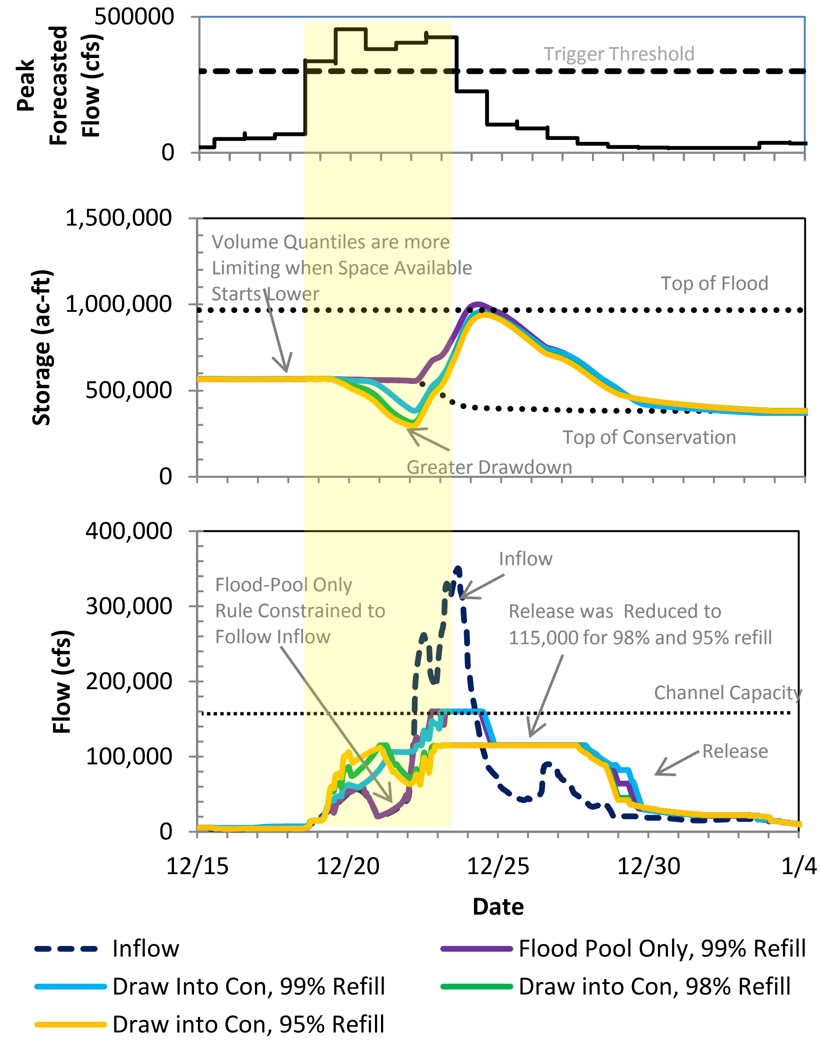

Figure 14(f)

Figure 14, continued

200-year 1965 Shape, 600 TAF Starting Storage

200-year 1965 Shape, 400 TAF Starting Storage

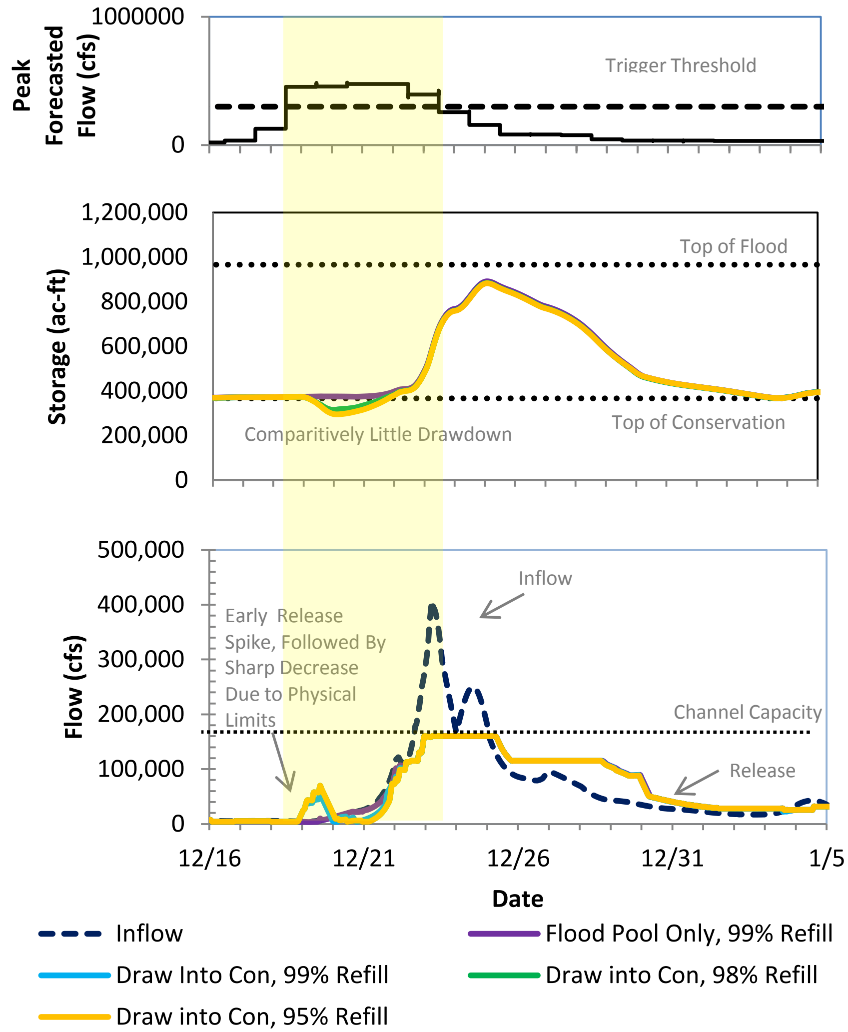

Figure 14(g)

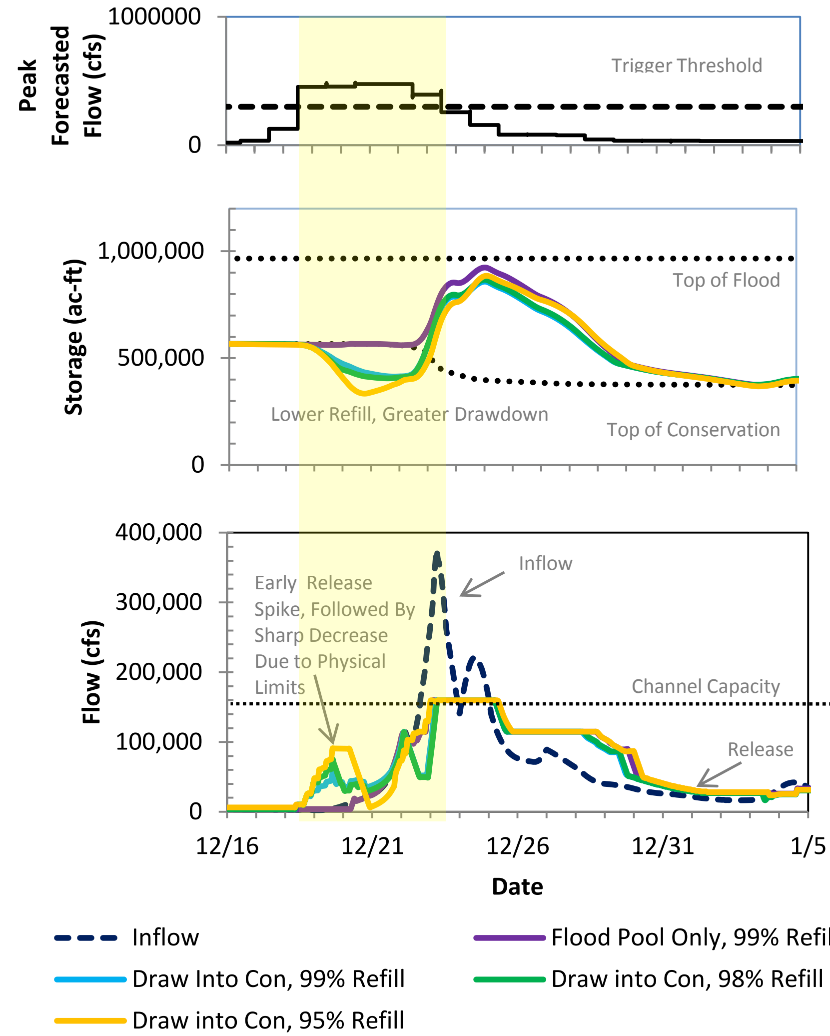

Figure 14 (h)

Figure 14, continued

200-year 1986 Shape, 600 TAF Starting Storage

200-year 1986 Shape, 400 TAF Starting Storage

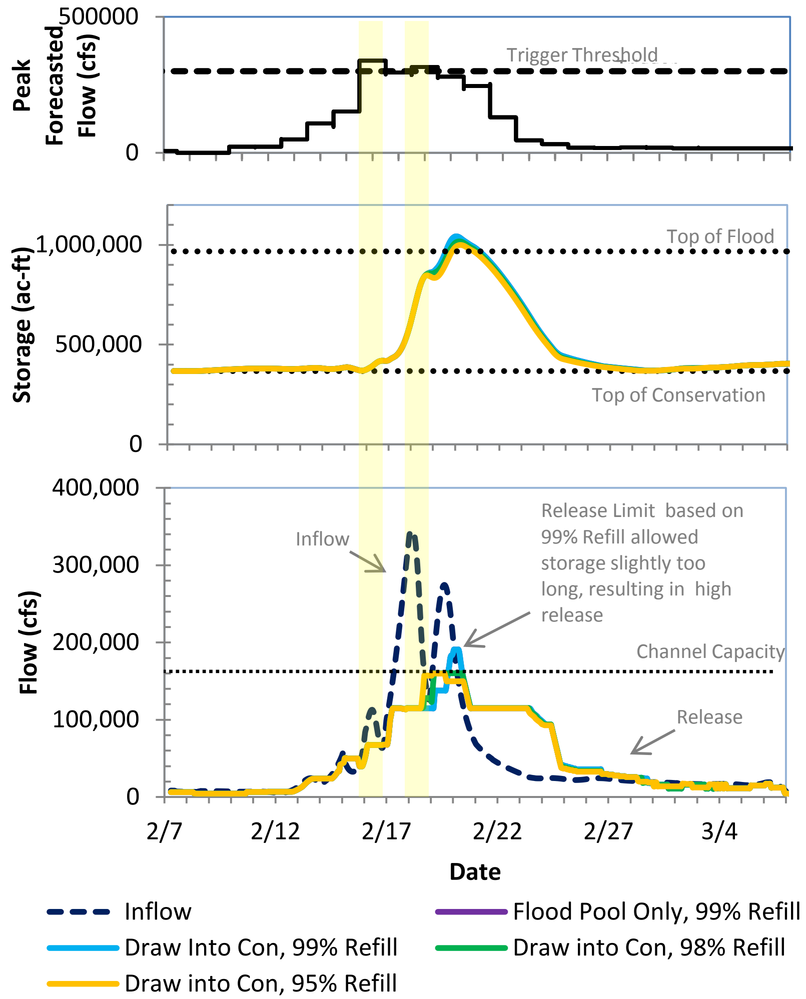

Figure 14(i)

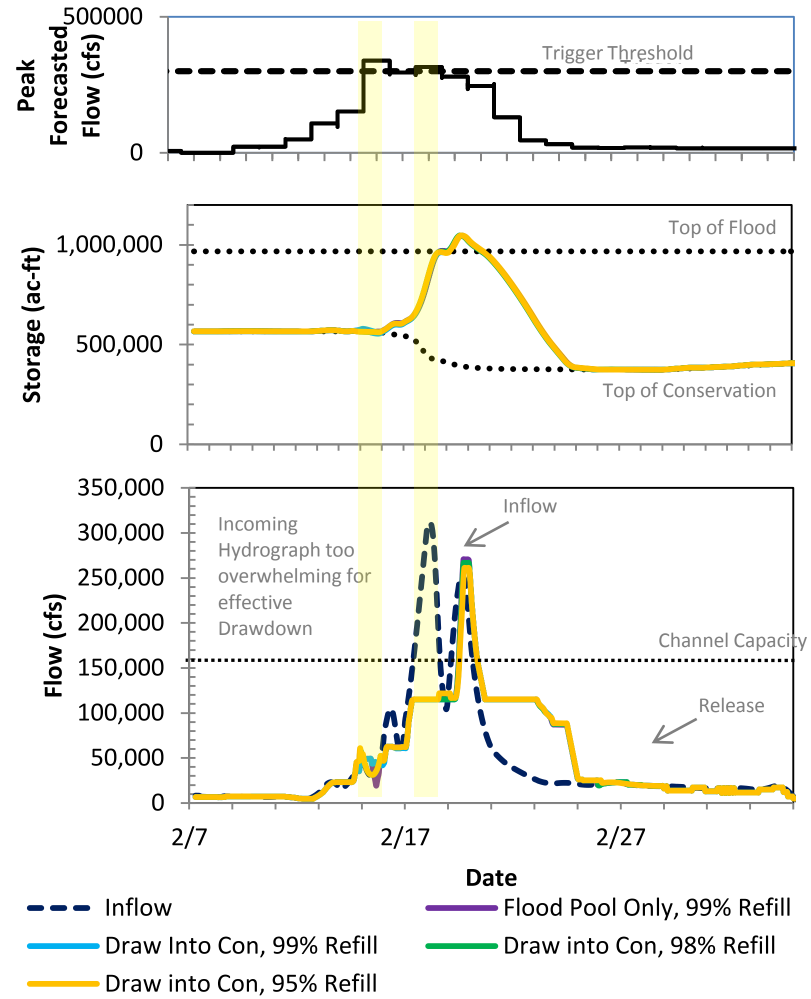

Figure 14(j)

Figure 14, continued

200-year 1997 Shape, 600 TAF Starting Storage

200-year 1997 Shape, 400 TAF Starting Storage

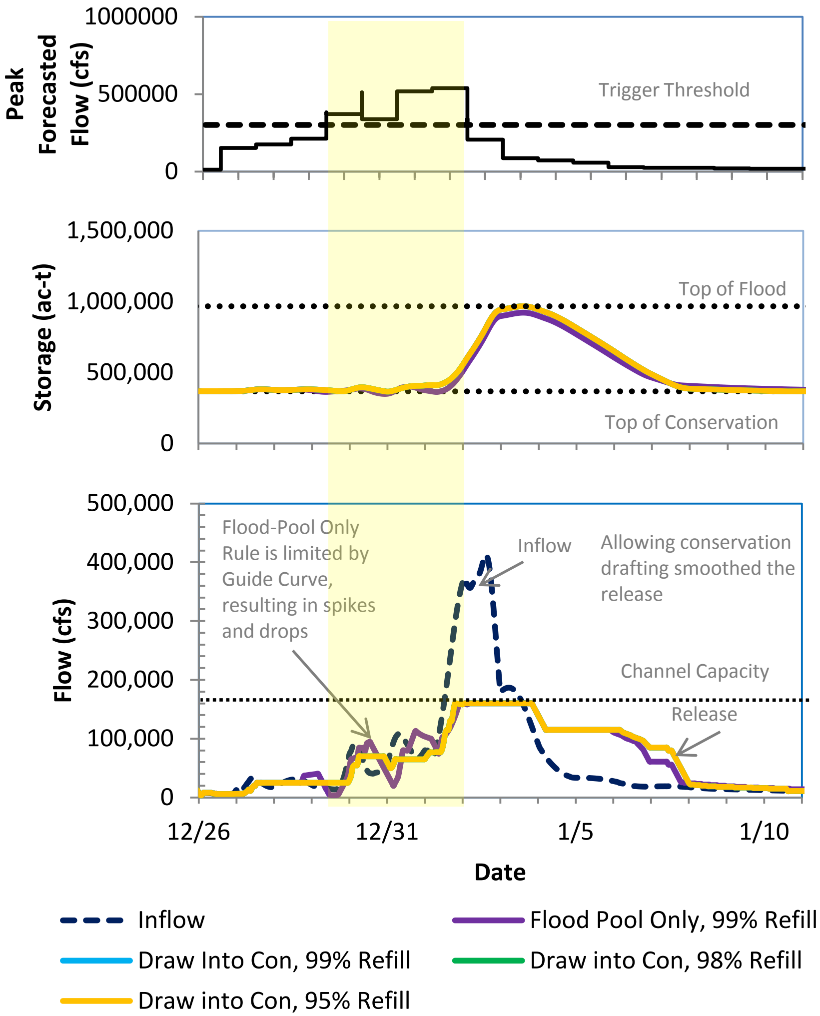

Figure 14 (k)

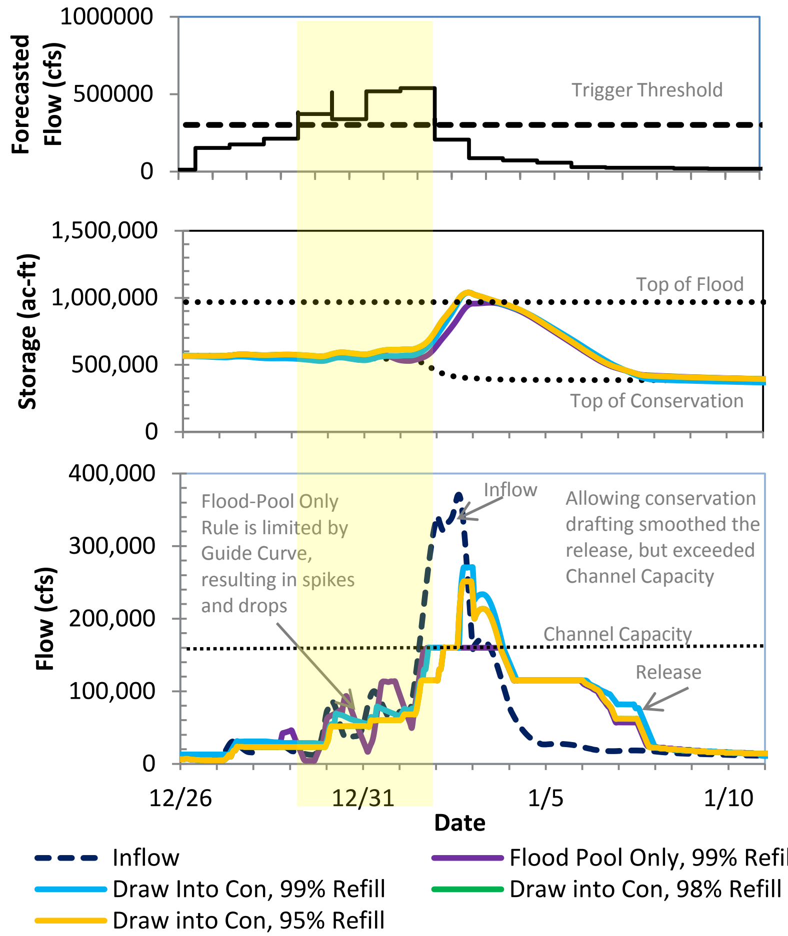

Figure 14 (l)

Figure 14, continued

Table 8a. Results by Event for 99% Refill Probability, Allowing/Not Allowing Conservation Releases. Maximum Initial Storage Space in Flood Pool.

600 TAF initial Stor	PMF	PMF	SPF	SPF	1955	1955	1964	1964	1986	1986	1997	1997
Use Con?	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Refill Probability	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%
Peak Storage (TAF)	893.1	961.4	1,003	1,003	908.4	952.3	885.1	891.8	1043	1043	966.8	922.7
Peak Outflow (kcfs)	160	160	160	160	160	160	160	160	**191**	**191**	160	160
Duration >115 kcfs (hr)	63	59	53	53	50	58	72	72	143	143	61	61
Duration >160 kcfs (hr)	0	0	0	0	0	0	0	0	16	16	0	0
Failure Probability	8%	9%	7%	7%	7%	7%	10%	10%	**100%**	**100%**	9%	9%

Table 8b. Results by Event for 99% Refill Probability, Allowing/Not Allowing Conservation Releases. Minimum Initial Storage Space in Flood Pool

400 TAF Initial Stor	PMF	PMF	SPF	SPF	1955	1955	1964	1964	1986	1986	1997	1997
Use Con?	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Refill Probability	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%	99%
Peak Storage (TAF)	937.1	970.4	1,021	1,021	956.0	999.4	1050	1050	1053	1053	1038	963.5
Peak Outflow (kcfs)	160	160	**191**	**191**	160	160	160	160	**265**	**271**	**271**	160
Duration >115 kcfs (hr)	61	61	59	59	58	61	61	66	137	39	61	61
Duration >160 kcfs (hr)	0	0	15	15	0	0	0	0	20	21	29	0
Failure Probability	8%	9%	**100%**	**100%**	7%	7%	10%	10%	**100%**	**100%**	**100%**	10%

For the PMF, 1955, and 1997 shapes under both initial conditions and the artificial "on-time" forecast (Appendix B), the rule which did not allow conservation pool drafting rapidly decreased to zero release and release was constrained to rise with the rising limb of the hydrograph. The rule was limited by the guide curve specifying TOC; since inflow was low, the allowed release was low in spite of forecasts.

The rules which did allow drafting into the conservation pool with various refill probabilities were able to respond to the forecasted rise in inflow, and sustained the higher releases to varying degrees. The rule with 99% refill probability responded the most conservatively, but did not allow the releases to drop to zero. Overall storage in the reservoir was lower, although peak releases and durations were unaffected.

The 1965 shape demonstrates how drafting into the conservation pool can have risks beyond risks to water supply--the releases for 95% and 98% refill probabilities spiked on 12/19, and then suddenly decreased, perhaps due to physical constraints and inability to release at that elevation. This early spike is undesirable for downstream warning, and a slower ramping-up of releases would have sufficed to pass the flood. Increases in early releases did not drastically change the peak reservoir elevation or release rate, so there were no flood control benefits. This spike did not occur in the original HEC simulations of the advance release rule with conservation drafting (USACE 2003) and was an unintended outcome of the present study's simulations. The modified HEC rule as described in this thesis may require further release limits to avoid undesirable spikes. Release limits could be refined in future studies to specify the maximum volume that can be drafted and a constant release to evacuate this volume.

Allowing conservation releases proved beneficial in reducing peak flows for 1986, the double peaked event. However, in general, the releases from the conservation zone reduced the peak storage in the reservoir without reducing or delaying peak releases.

USACE policy does not allow use of the conservation pool, and so further rules including conservation pool releases were not evaluated. Preliminary results are inconclusive about whether the release of conservation pool water would provide significant peak reduction for a variety of shapes and initial conditions. Future studies should evaluate the possibility of allowing the forecast-based rule to release water to the lowest guide curve (600 TAF flood space), if the current space in the flood pool is at less than its maximum. The reoperation study for Folsom is considering rules based on basin wetness which could raise or lower the guide curve (decrease or increase the flood space). Allowing forecast releases to bring the flood storage back to 600 TAF regardless of the upstream credits or basin wetness indices would be an important feature if these rules are implemented.

7.3. Sensitivity to Refill Probability

The results from the HEC (2002) rule formulation with 600 TAF starting storage—flood pool with maximum storage space—are listed in Figure 15 with varying refill probabilities. The simulation used the artificial "on-time" forecast (Appendix B). The shapes of interest for the 200-year flood with a flood pool starting at maximum available space were 1986 and 1955; without the use of forecasts for these shapes, the model predicts flows exceeding 160,000 cfs. With a 98% refill probability (2% quantile), the peak was reduced to 160,000. Although the peak was not reduced below 160,000 for 1997 and 1964 shapes, implementing forecasts for the 1997 shape reduced the duration of flows by 2-3 hours. Similarly, in 1986 and 1955 the durations above 160,000 were reduced.

To test the rule (from HEC, 2002) further, the computations were then initialized with a smaller starting flood pool of 400 TAF and zero available storage credit upstream, using the same artificial forecasts (the "on-time" forecast, Appendix B). Reduction in peak was much more pronounced; for all shapes except 1986 the forecast-based operations reduced the peak flow below channel capacity. Durations above 160,000 were generally decreased (Figure 15).

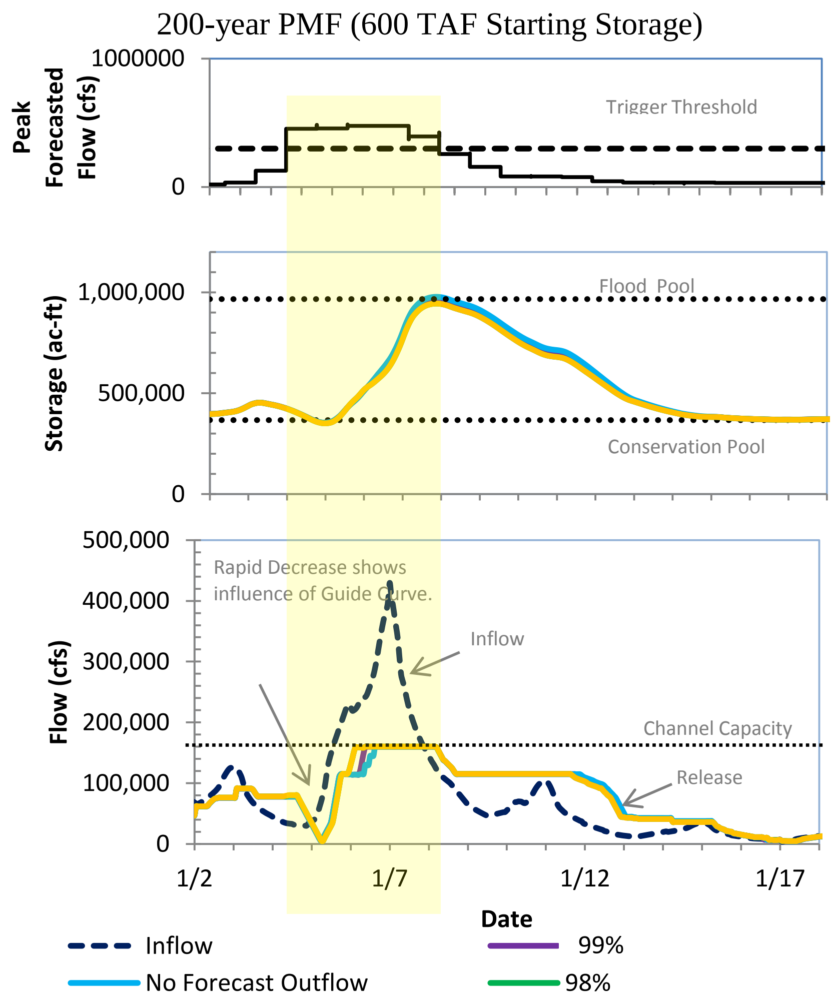

Figure **15**a

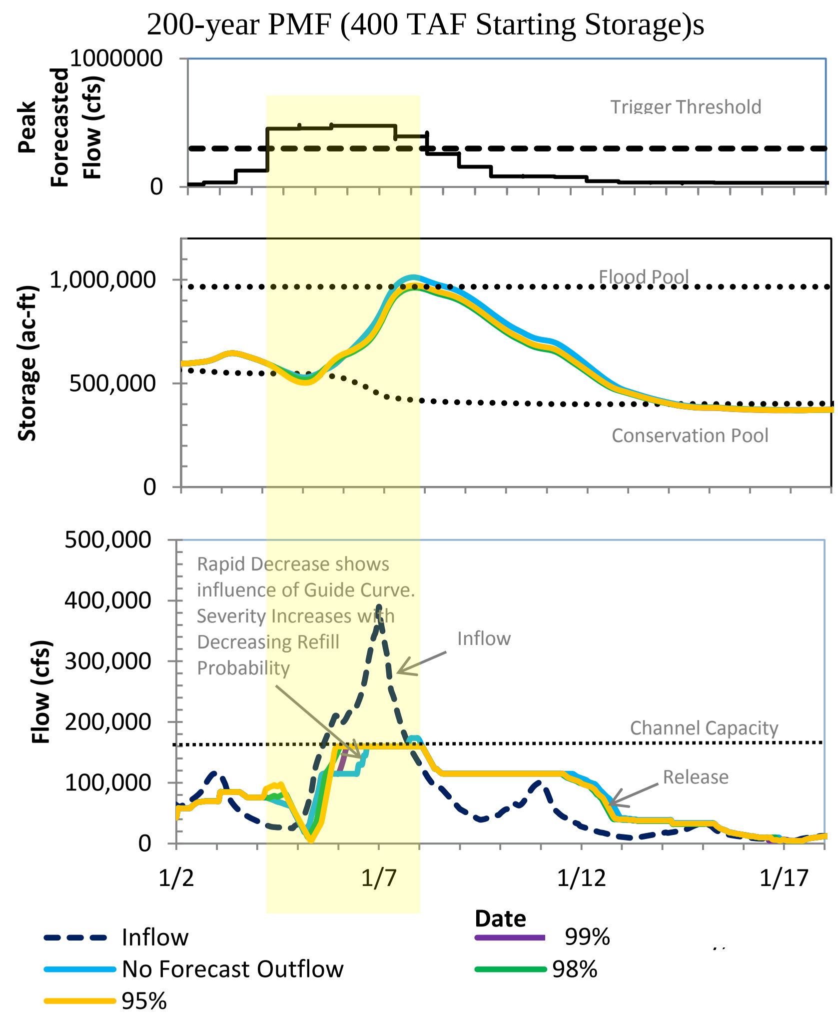

Figure **15**b

Figure 15. Sensitivity to Refill Probability for Different Hydrograph Shapes

200-year SPF (600 TAF Starting Storage)

200-year SPF (400 TAF Starting Storage)

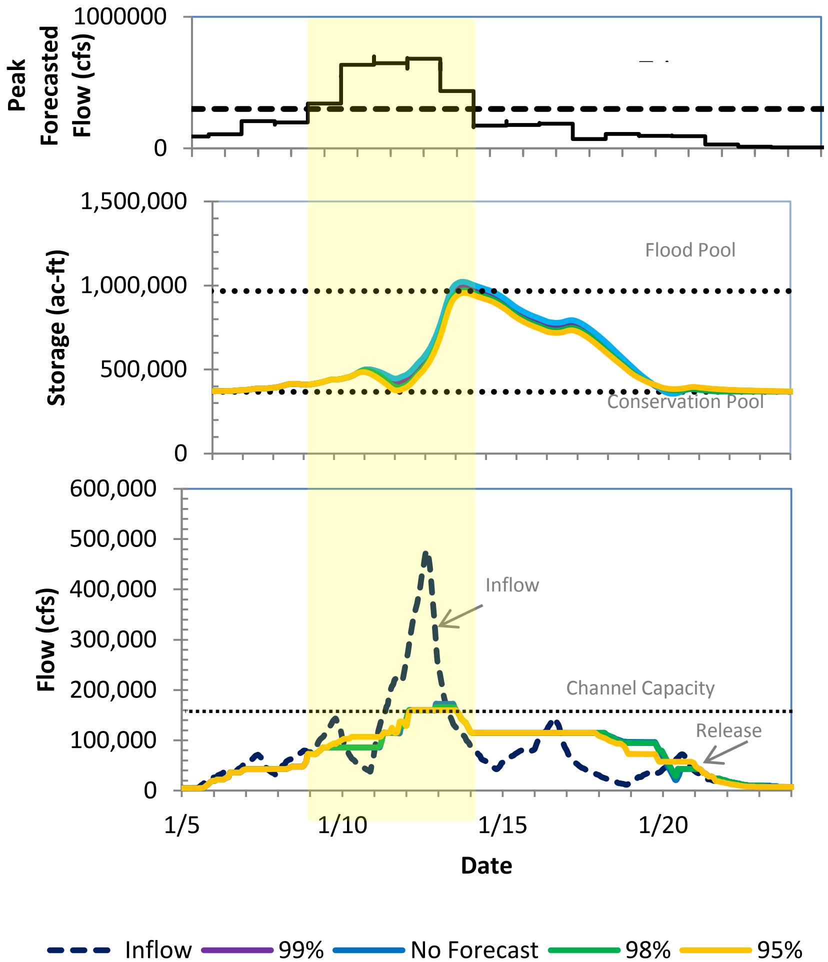

Figure **15**c

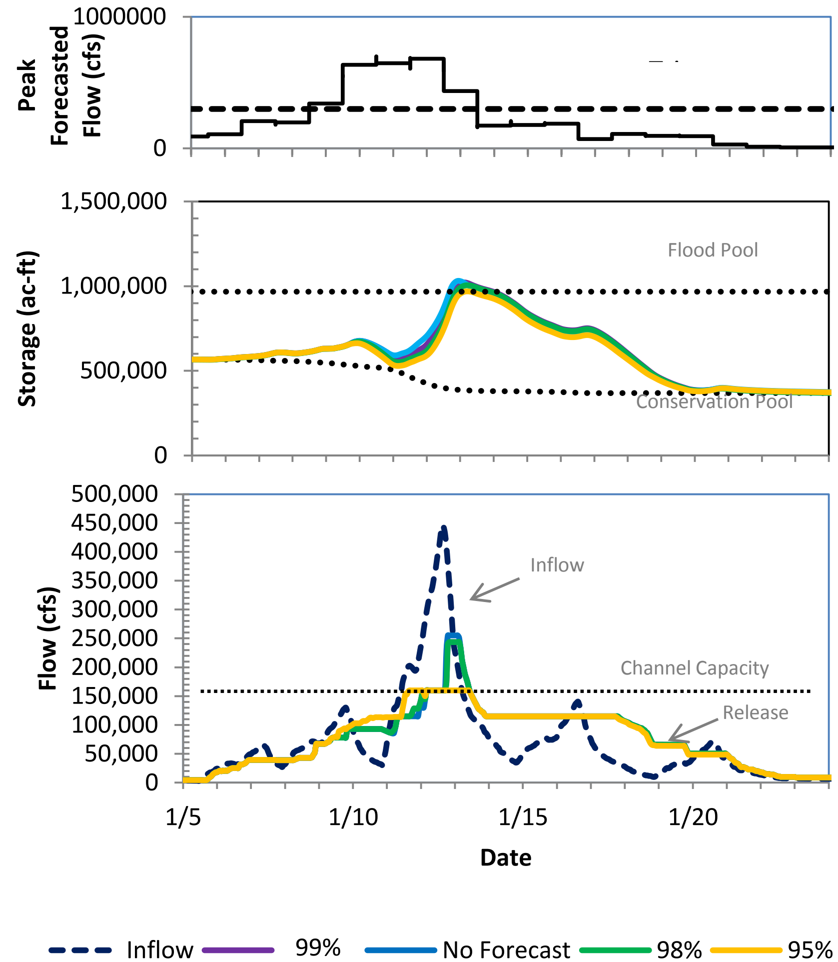

Figure **15**d

Figure 15, Continued

200-year 1955 (600 TAF Starting Storage)

200-year 1955 (400 TAF Starting Storage)

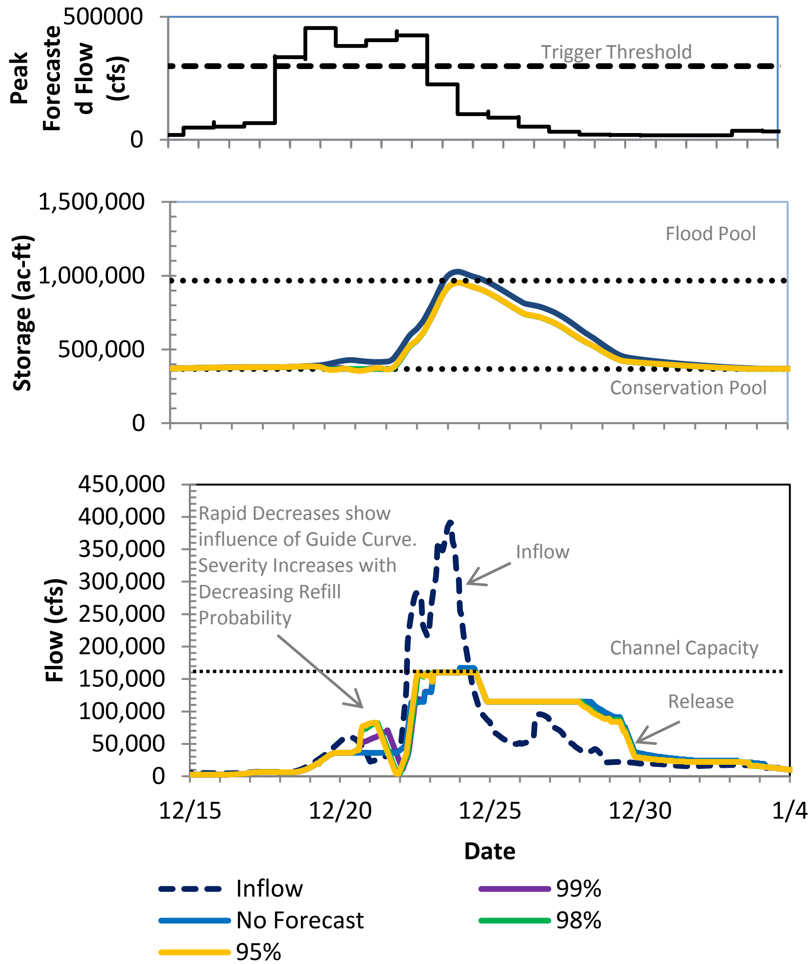

Figure **15**e

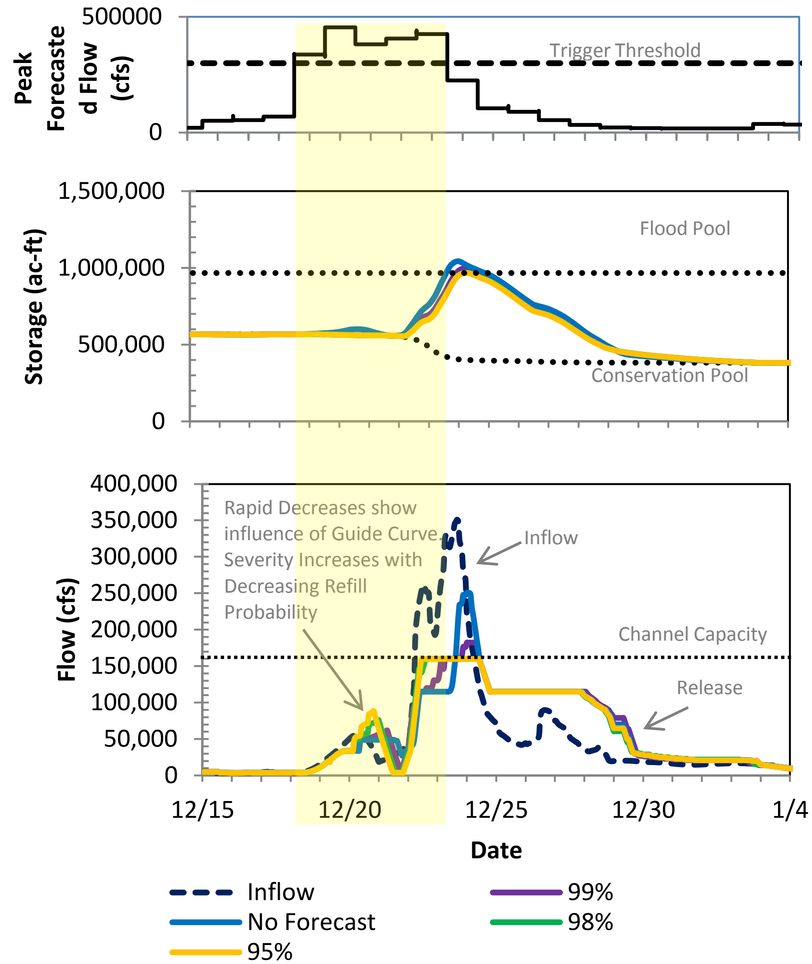

Figure **15**f

Figure 15, Continued

200-year 1964 (600 TAF Starting Storage)

200-year 1964 (400 TAF Starting Storage)

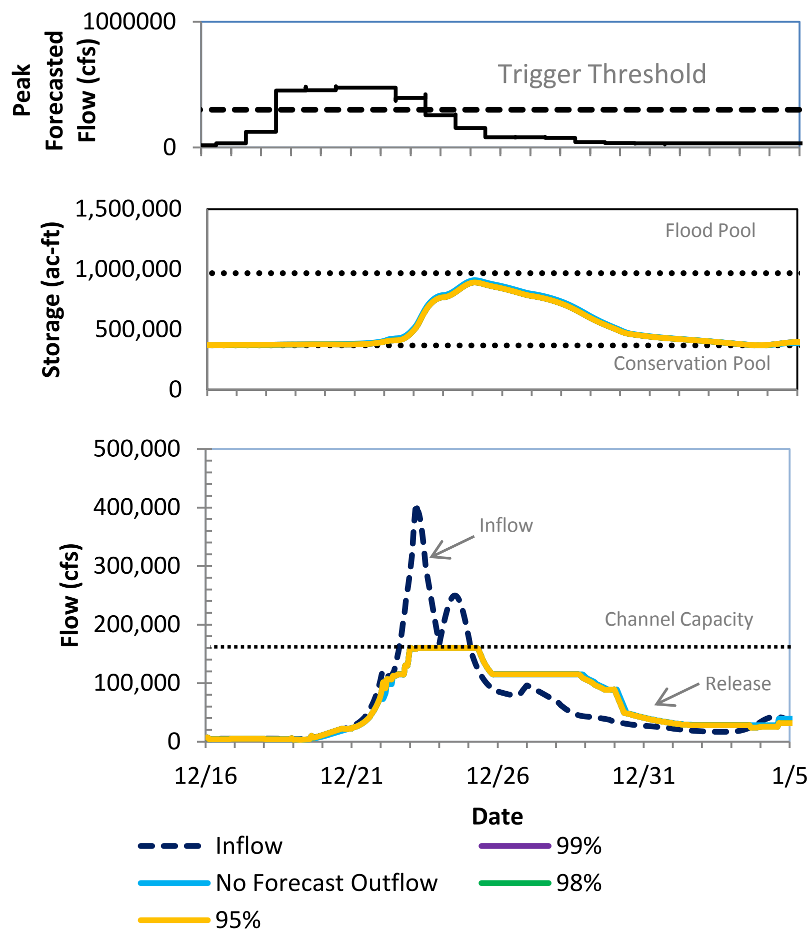

Figure **15**g

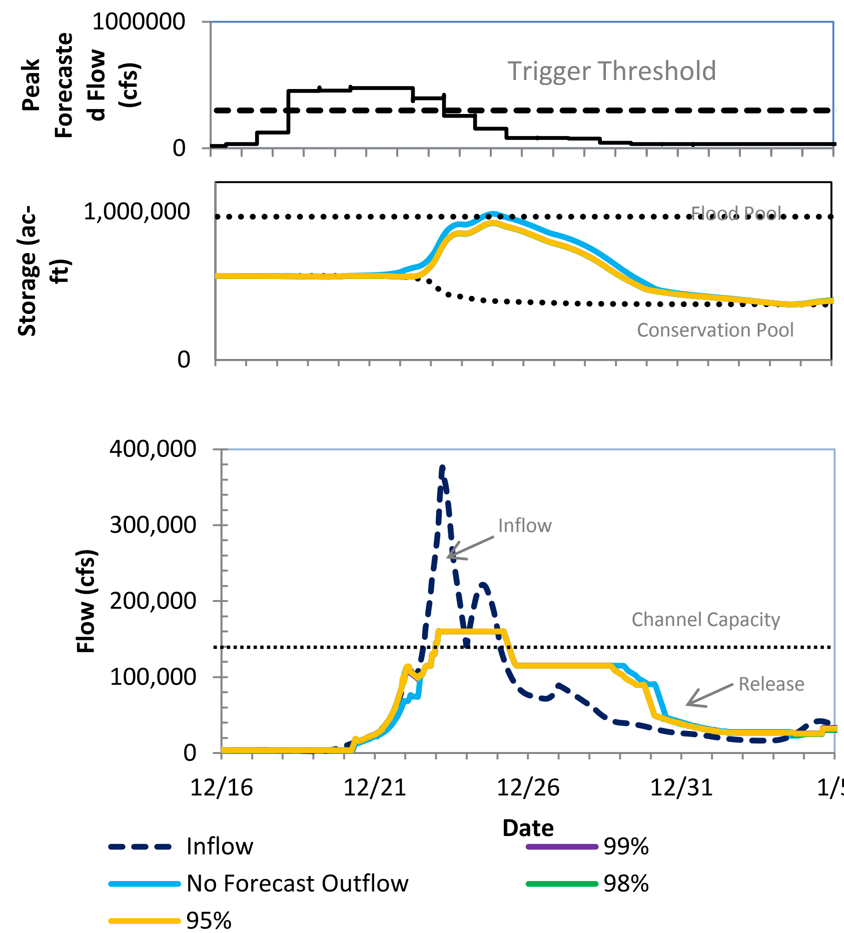

Figure **15**h

Figure 15, Continued

200-year 1986 (600 TAF Starting Storage)

200-year 1986 (400 TAF Starting Storage)

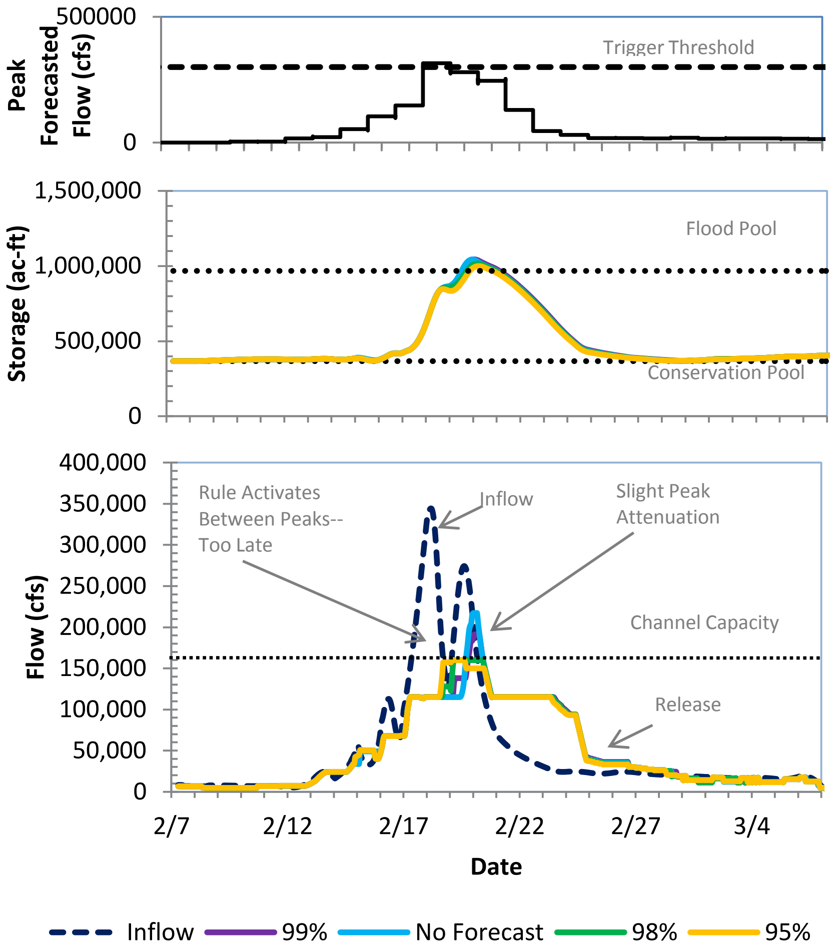

Figure **15**i

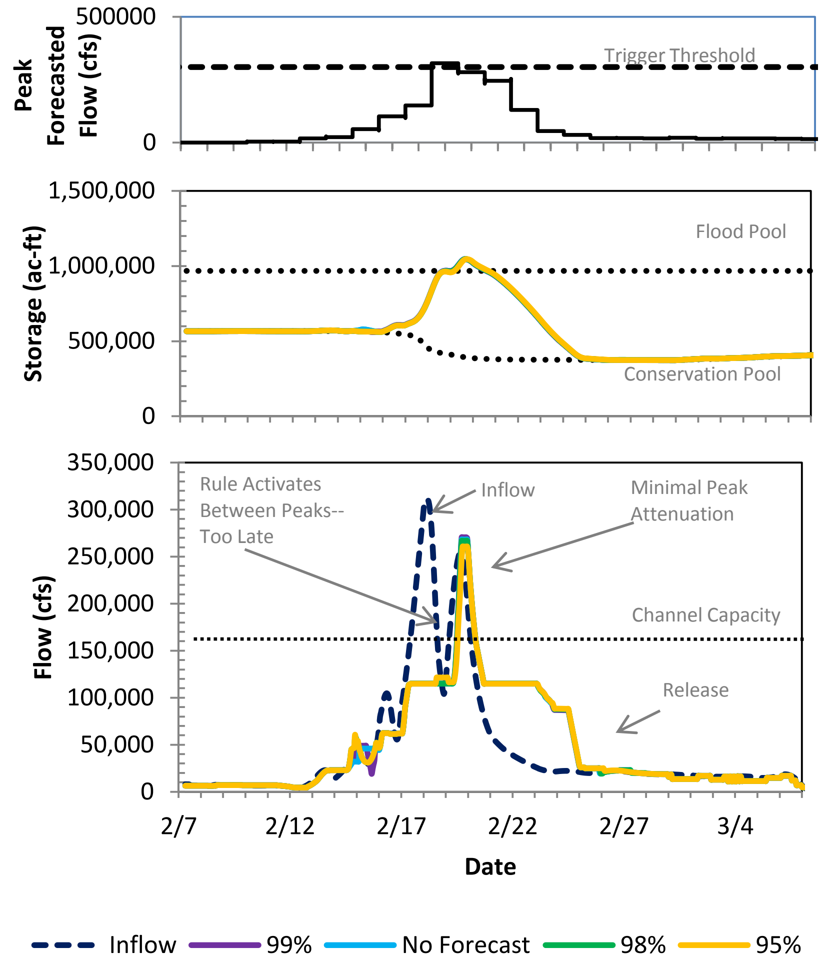

Figure **15**j

Figure 15, Continued

200-year 1997 (600 TAF Starting Storage)

200-year 1997 (400 TAF Starting Storage)

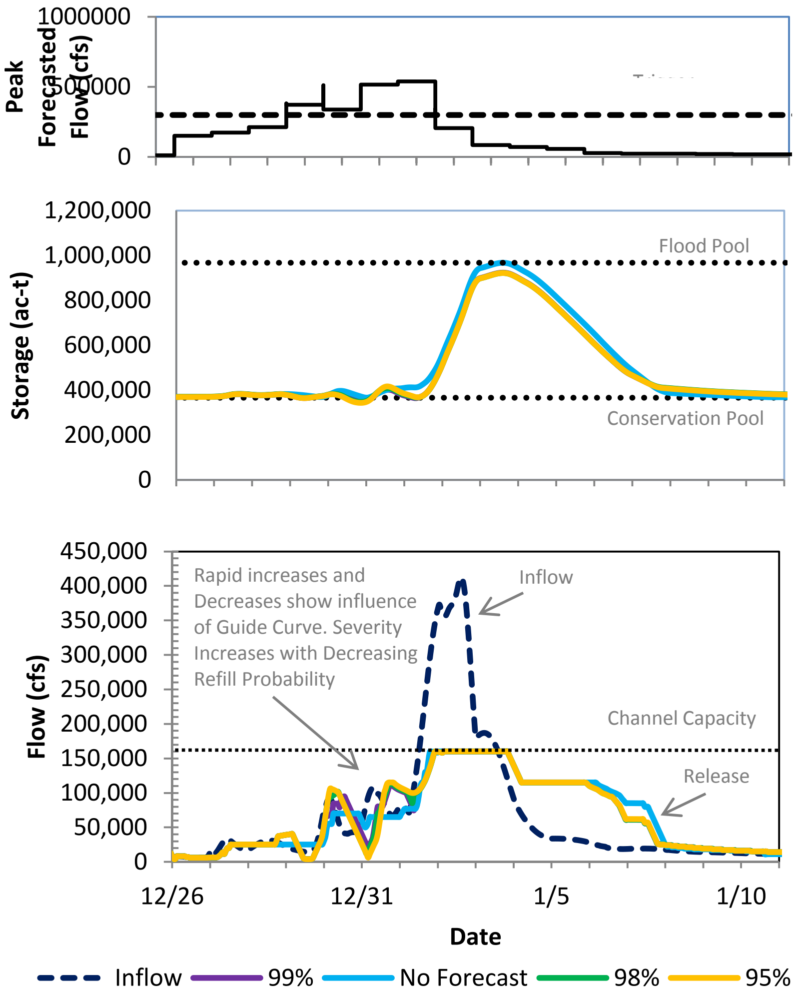

Figure 15k

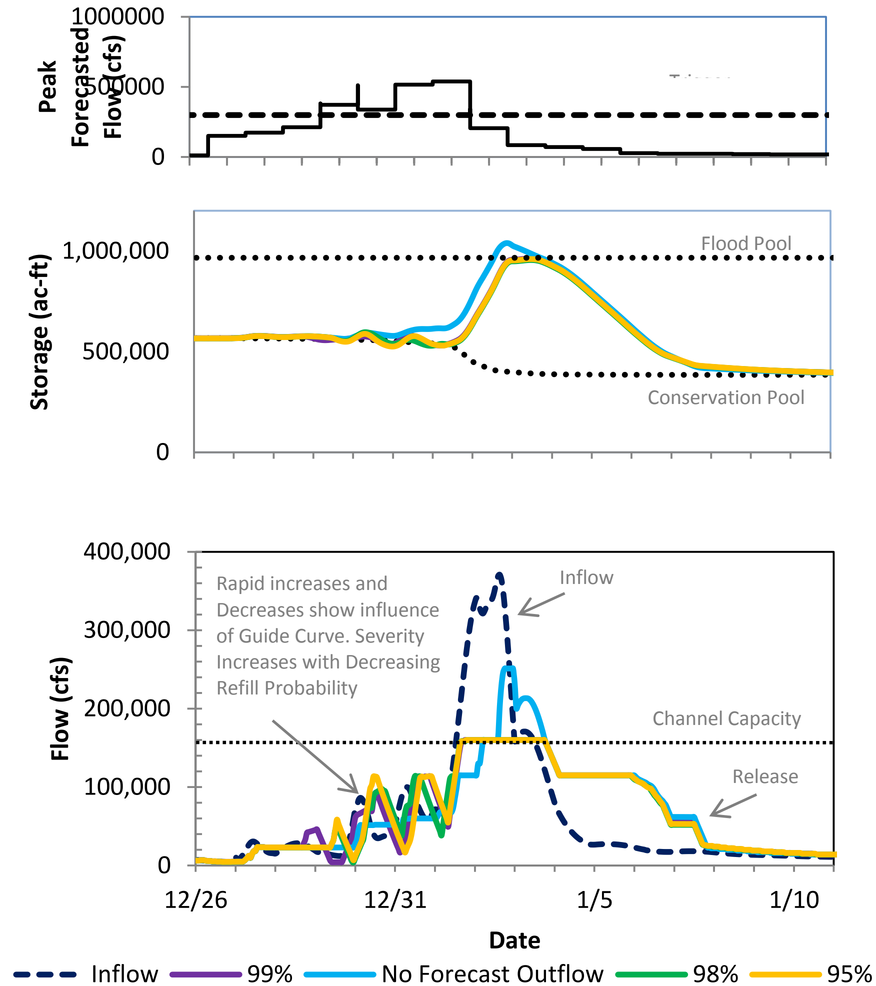

Figure 15l

Figure 15, Continued

The rules are most aggressive and effective when the flood pool is at its minimum storage space, but the reservoir is not full; the reservoir has room to store water and attenuate outflows for floods of the size considered (approximately 200-year floods). Since most of the simulations starting with maximum storage space in the flood pool could already pass the 200-year flood, and since the only opportunity to release based on forecasts in this scenario is to match inflow, the forecast operations were not needed and provided little benefit compared to the normal operation. Further, as discussed in the previous section, the simulations for the PMF, 1955, and 1997 shapes are constrained by the guide curve, leading to rapid decreases in releases, and then increases as inflow rises.

However, it was important to demonstrate that the forecast rules did not hinder the reservoir's ability to pass the 200-year event with the flood pool initialized with maximum space in the flood pool. For double peaked events, the simulations starting with maximum space in the flood pool showed some benefits from forecast-based operations; during double peaked floods such as 1986, normal operations would not react to the second wave and would try to reduce releases too soon, whereas forecast-based operations would sustain releases in advance of the second wave.

Regardless of the starting location in the flood pool, reducing the refill probability from 99% to 98% or 95% increases the initial advance release; the lower the refill probability, the higher the initial advance release. During the flood itself (after the advance release is over) operations with lower refill probabilities typically have lower outflows.

7.4. Operating Results and Forecast Variability

Thus far, the thesis has discussed only one forecast set (the "on-time" forecast, Appendix B), distributed so some forecasts are late, some are early, some are low, and some are high; the set as a whole is neither more likely to be late than early nor more likely to be high than low. However, forecasts can turn out many different ways. For each 200-year event shape, artificial forecasts were generated for each of the following cases: entire forecast set late by 12 hours, entire forecast set early by 12 hours, 500-year forecasted event, and 100-year forecasted event. The high, low, late, and early artificial forecasts can be found in Appendix B alongside the "on-time" forecast.

7.4.1. Timing Error Sensitivity Analysis-Performance of Late Forecasts vs. Early Forecasts

The operational sensitivity to timing errors was shown by comparing simulations in which the forecast peaks were centered 12 hours earlier than the actual peak and 12 hours later than the actual peak. Early forecasts are plotted in red, and late forecasts are plotted in yellow for Figures Figure 16(a) through Figure 16(l). The results are summarized in Table 9a and Table 9b**.**

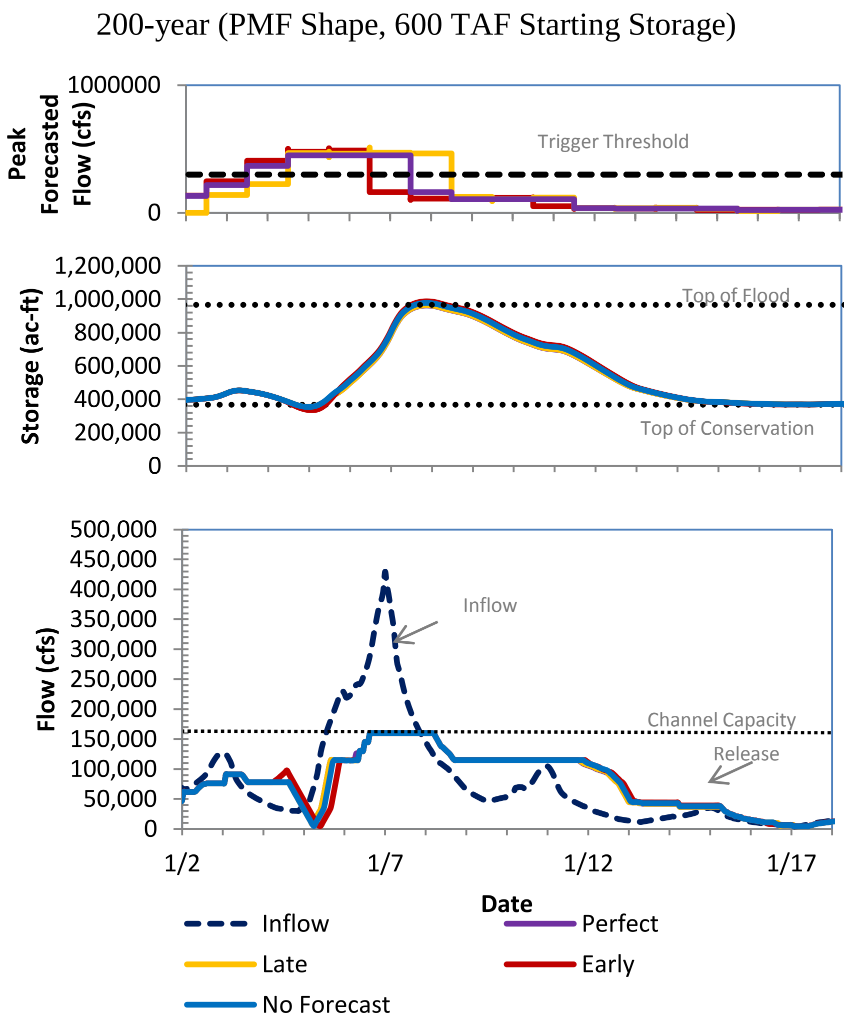

Figure 16(a)

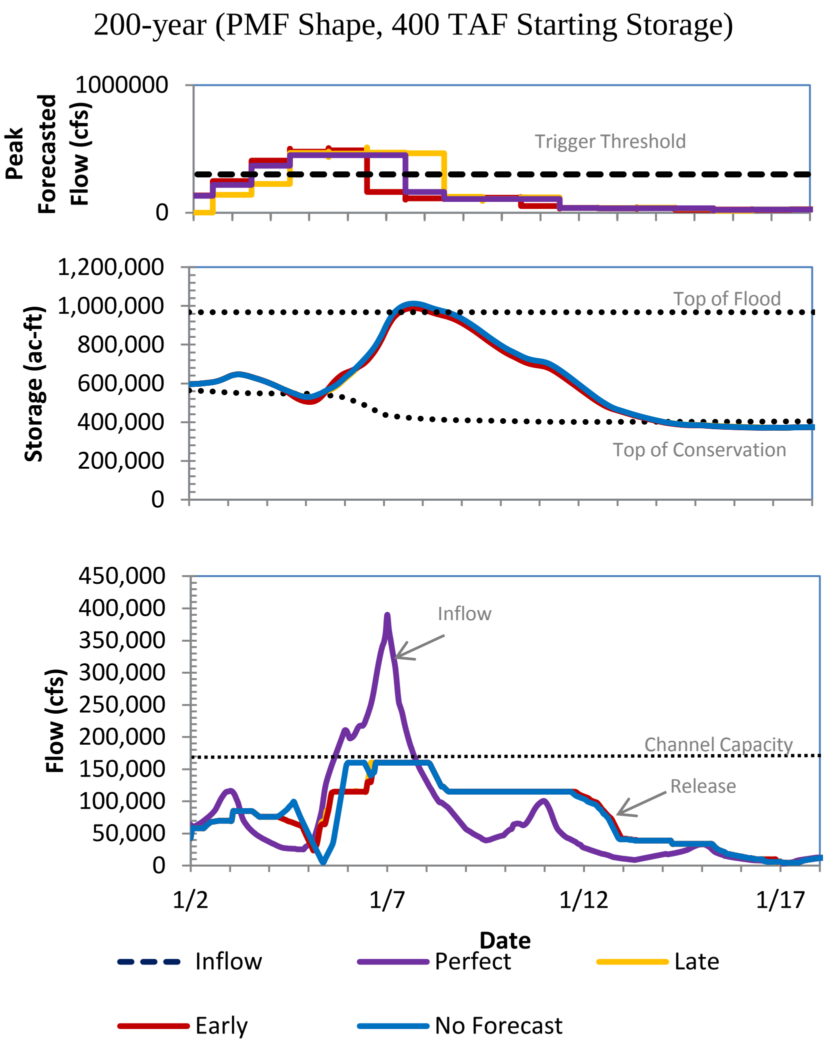

Figure 16(b)

Figure 16. 1-in-200 year operations-Sensitivity to Forecast Error

200-year (SPF Shape, 600 TAF Starting Storage)

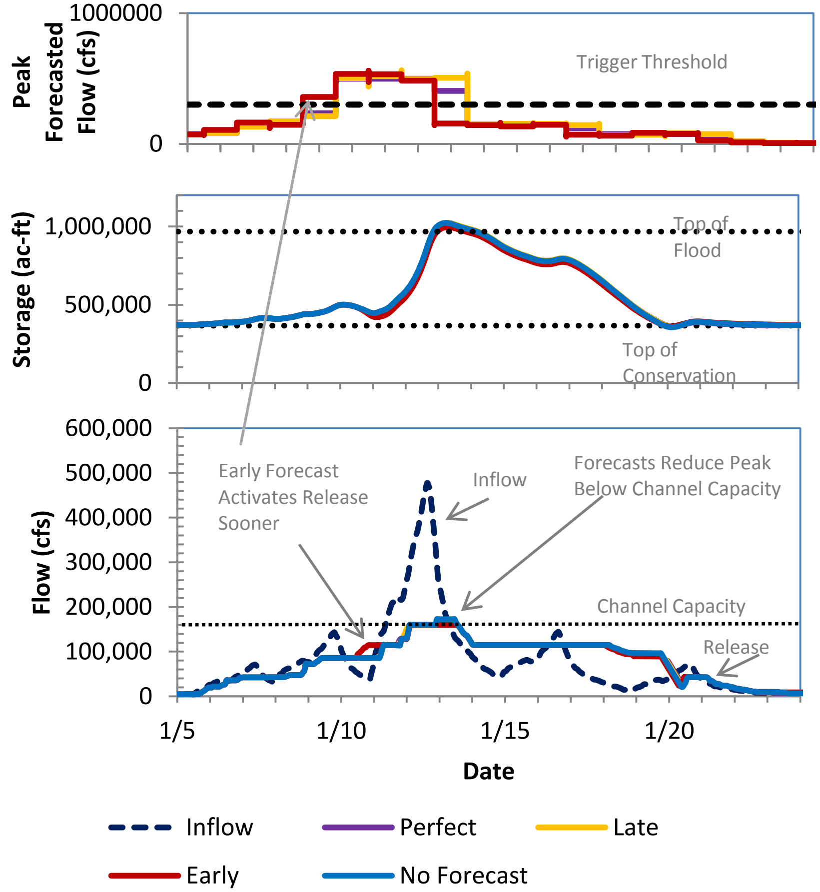

Figure 16(c)

200-year (SPF Shape, 400 TAF Starting Storage)

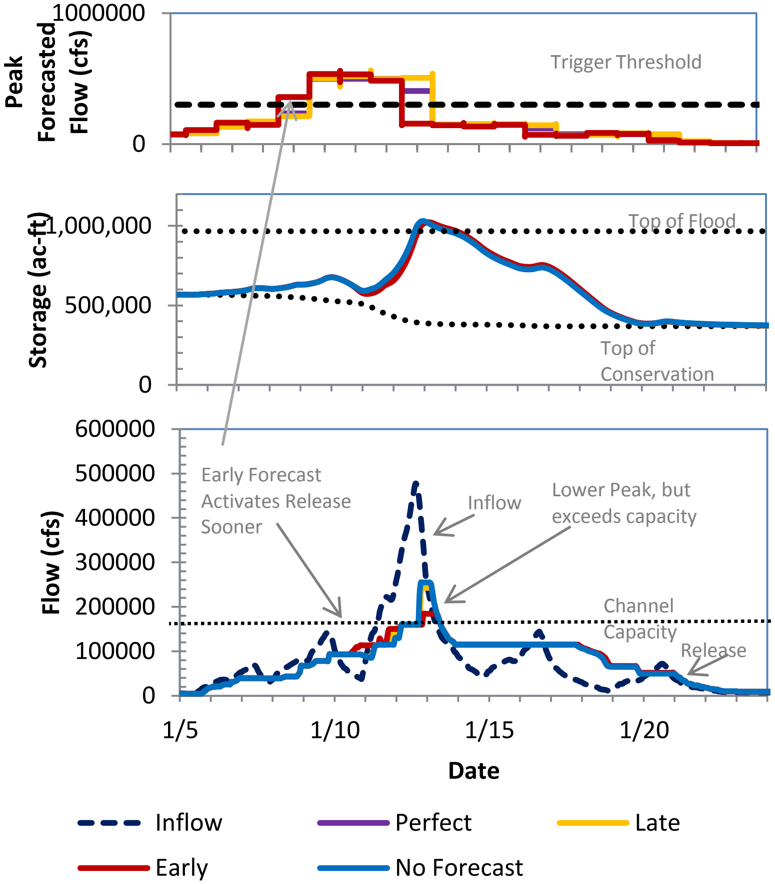

Figure 16(d)

Figure 16, Continued

200-year (1955 Shape, 600 TAF Starting Storage)

200-year (1955 Shape, 400 TAF Starting Storage)

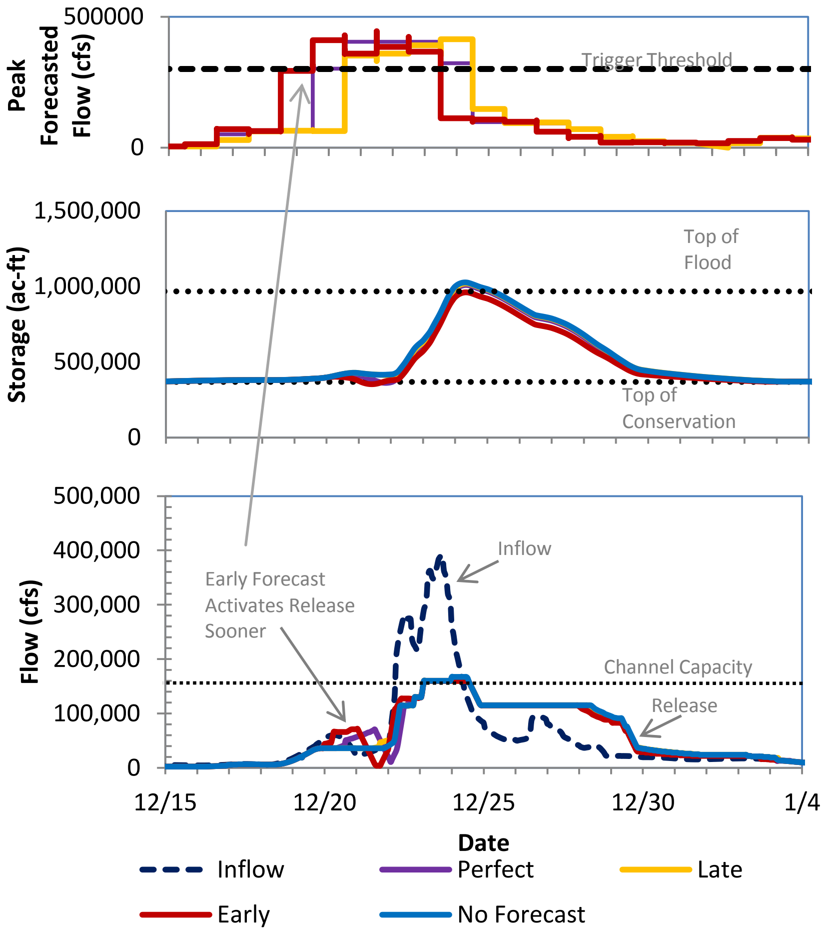

Figure 16(e)

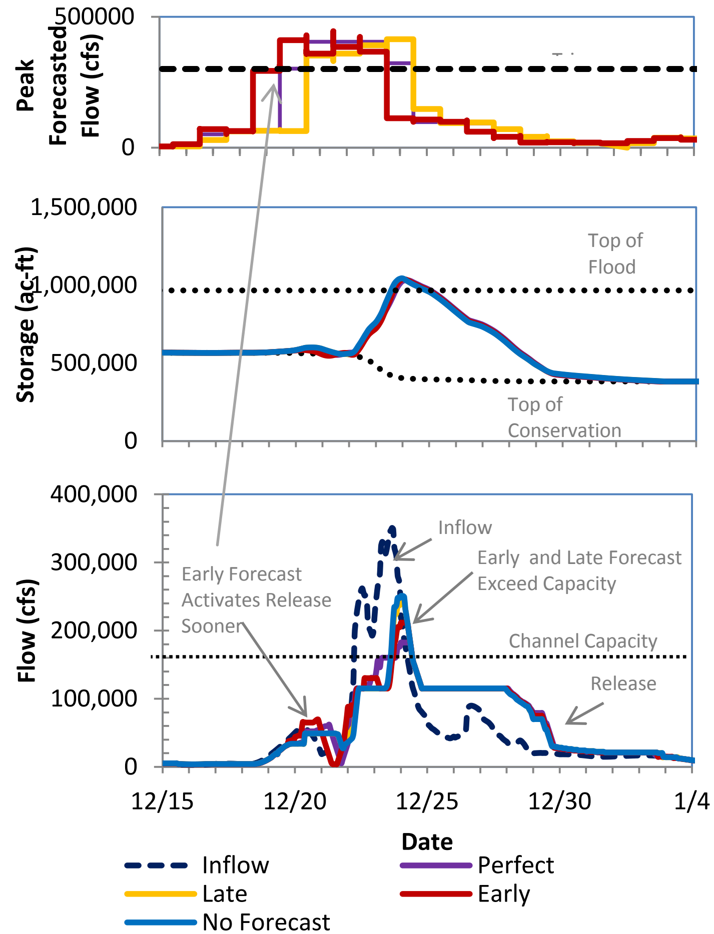

Figure 16(f)

Figure 16, Continued.

200-year (1965 Shape, 600 TAF Starting Storage)

200-year (1964 Shape, 400 TAF Starting Storage)

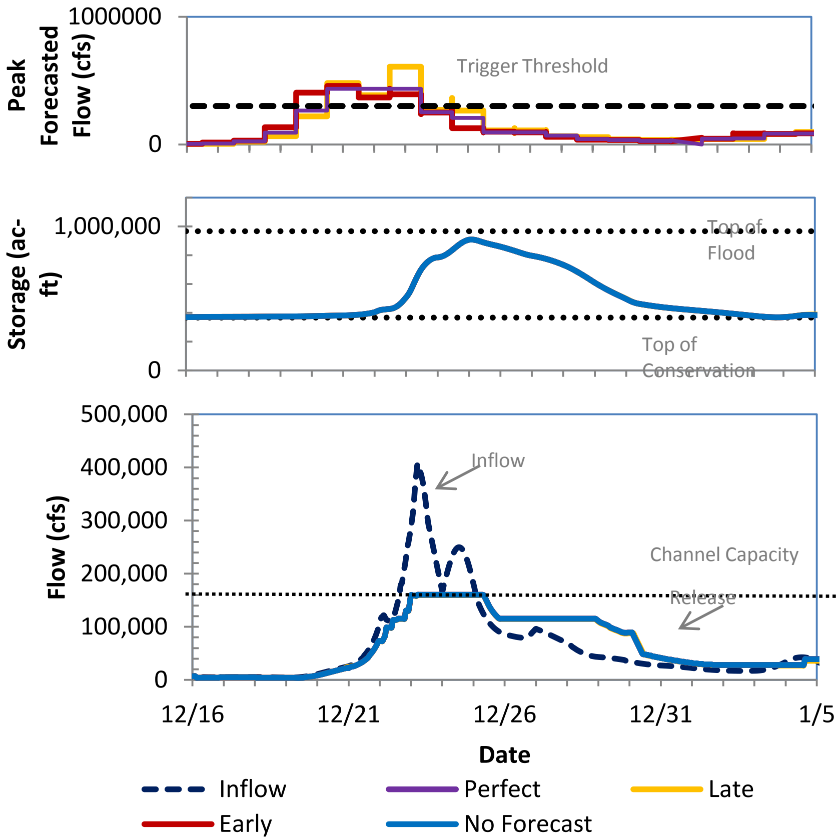

Figure 16(g)

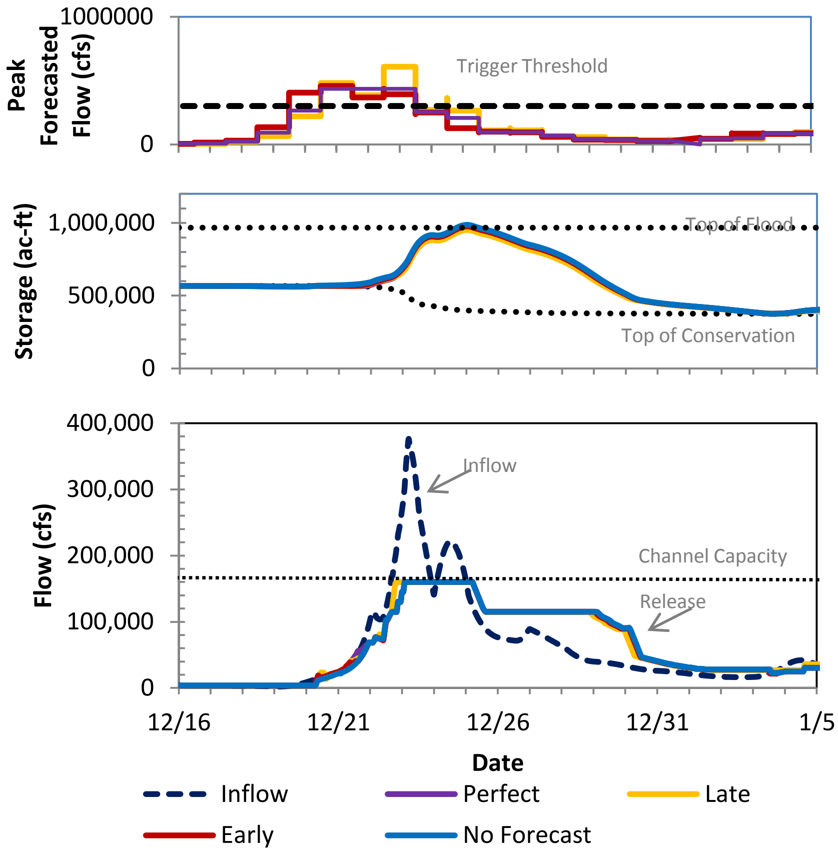

Figure 16(h)

Figure 16, Continued.

200-year (1986 Shape, 600 TAF Starting Storage)

200-year (1986 Shape, 400 TAF Starting Storage)

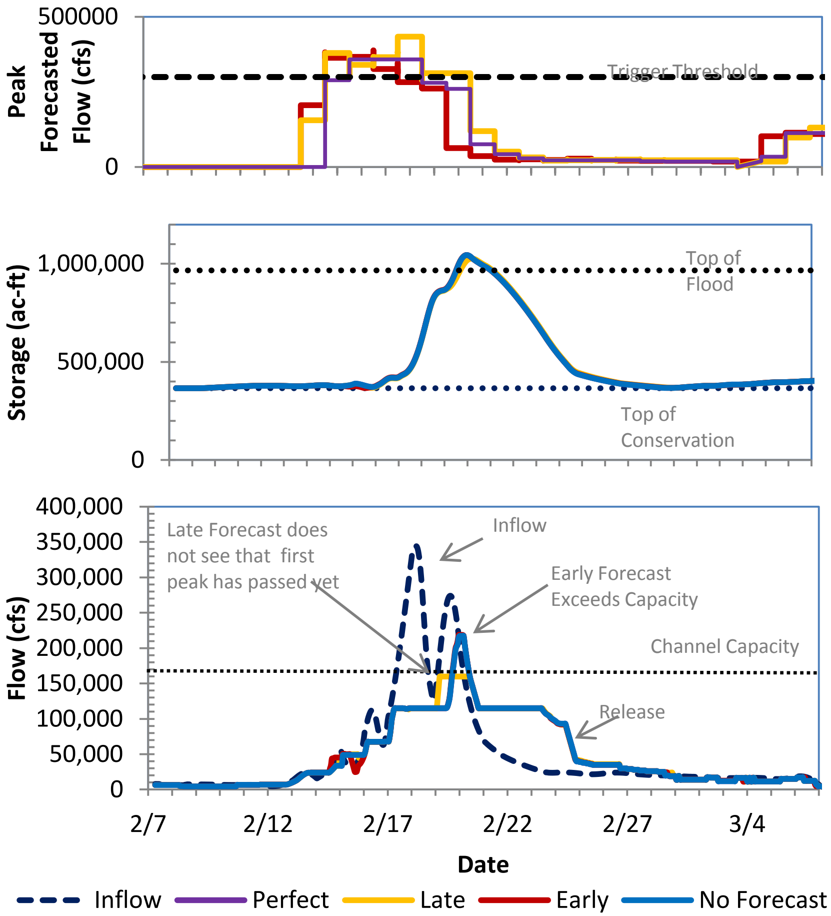

Figure 16(i)

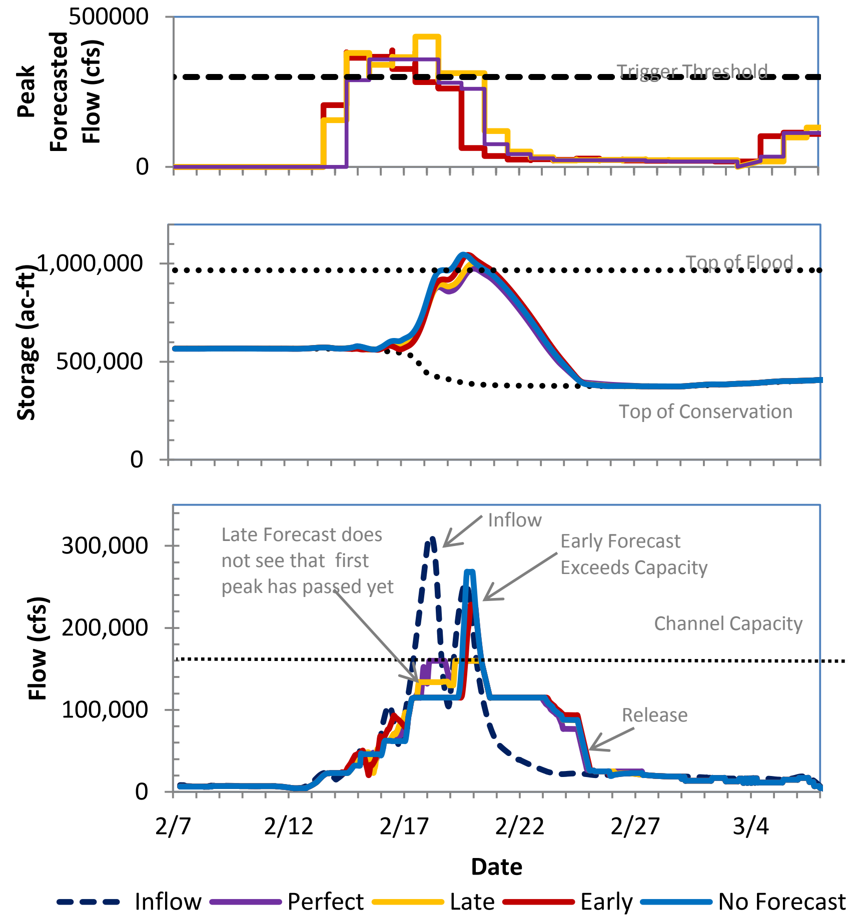

Figure 16(j)

Figure 16, Continued.

200-year (1997 Shape, 600 TAF Starting Storage)

200-year (1997 Shape, 400 TAF Starting Storage)

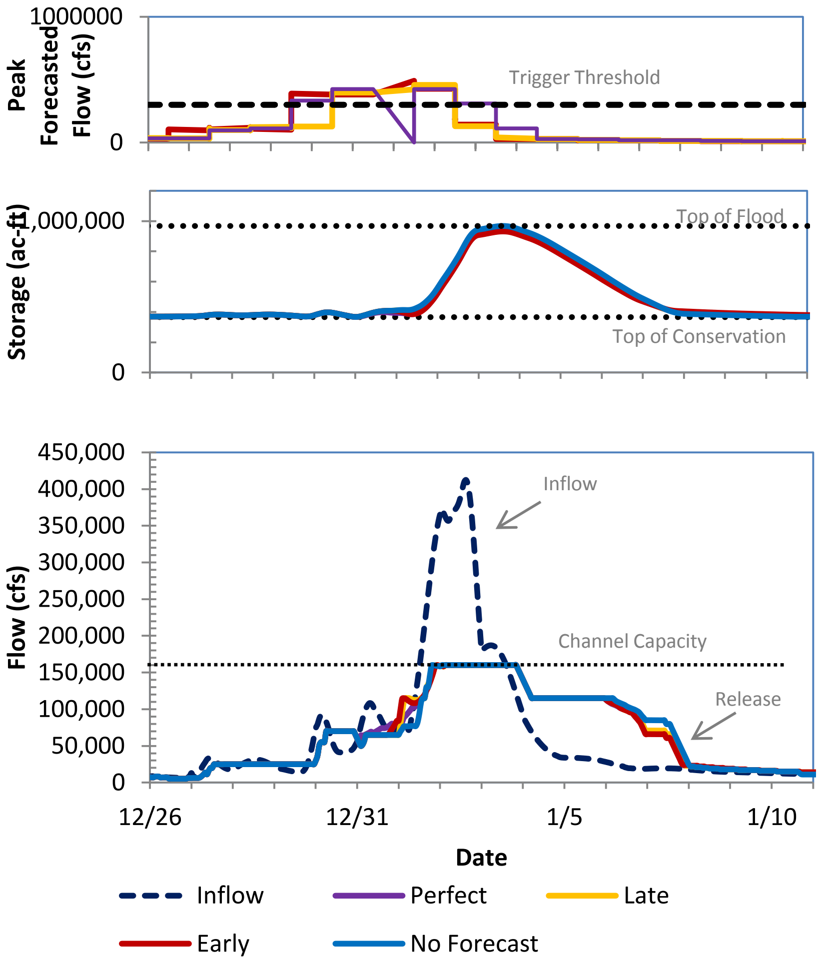

Figure 16(k)

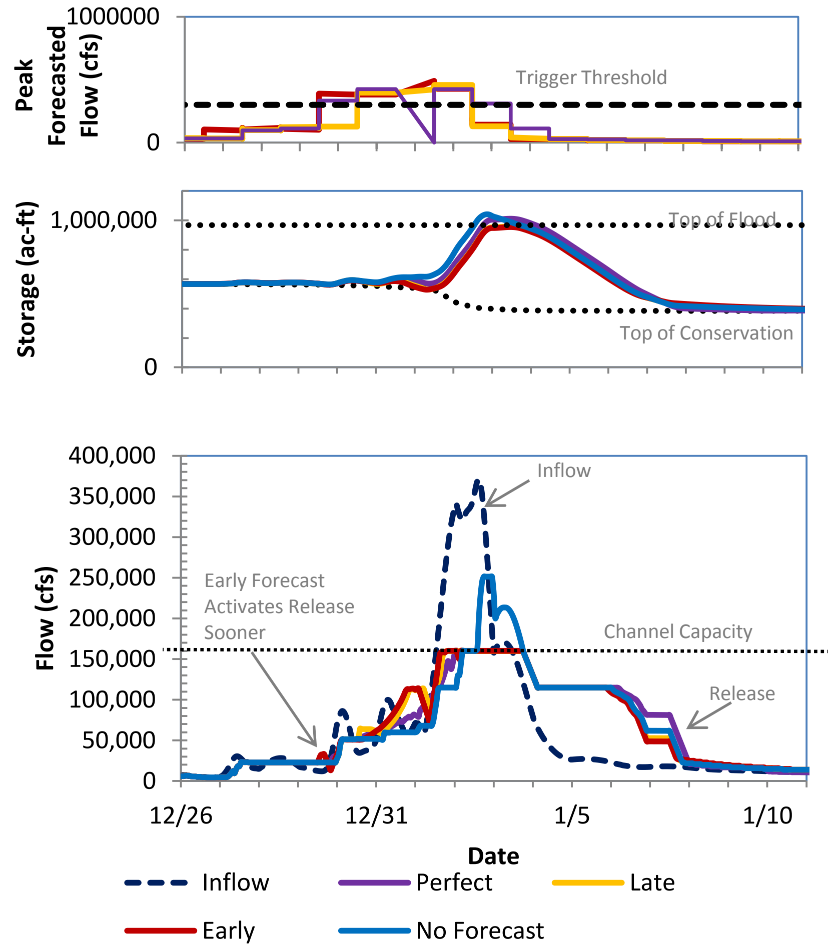

Figure 16(l)

Figure 16, Continued.

Table 9a Performance of Late and Early Forecasts

400	PMF	PMF	SPF	SPF	1955	1955	1964	1964	1986	1986	1997	1997
Error	Late	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late	Early
Peak Storage(ac-ft)	1,005	989.1	1,028	1,022	1,043	1,038	951.1	976.3	1,001	1,045	959.2	953.6
Peak Outflow(cfs)	160	160	**243**	**184**	**241**	**211**	160	160	160	**228**	160	160
Duration >115 kcfs (hr)	50	65	52	57	32	45	70	66	137	139	62	62
Duration >160 kcfs (hr)	0	0	17	14	19	17	0	0	0	17	0	0
Failure Probability	7%	9%	**100%**	**100%**	**100%**	**100%**	11%	10%	12%	**100%**	9%	9%

Table 9b Performance of Late and Early Forecasts

600	PMF	PMF	SPF	SPF	1955	1955	1964	1964	1986	1986	1997	1997
Error	Late	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late	Early
Peak Storage(ac-ft)	963.7	987.5	1,023	996.5	1,020	961.3	907.5	908.2	1,027	1,044	937.9	931.8
Peak Outflow(cfs)	160	160	**164**	160	160	160	160	160	160	**218**	160	160
Duration >115 kcfs (hr)	56	56	55	53	55	50	72	72	41	32	61	63
Duration >160 kcfs (hr)	0	0	16	0	0	0	0	0	0	18	0	0
Failure Probability	8%	8%	**100%**	7%	7%	7%	10%	10%	9%	**100%**	9%	9%

Late forecasts challenge the reservoir by not initiating advance release; early forecasts challenge the reservoir by overestimating the space available in the flood pool and allowing the reservoir to fill too early. The simulations with late forecasts only allowed outflows above 160 kcfs for the SPF and 1955 shapes with 400 TAF starting flood pool and the SPF with 600 TAF starting flood pool. In these cases, no advance release was made, and the reservoir did not have flood space to store the incoming event. Early forecasts allowed outflows above 160 kcfs for the 1955 and SPF case with 400 TAF starting flood space and for both of the 1986 cases. Outflows above 160 kcfs occurred for the 1986 shape with early forecasts because the incoming volume was simply too large. Outflows exceeded 160 kcfs for the 1955 and SPF shapes because the early forecasts predicted a large incoming volume when the reservoir was low, and so predicted that sufficient space was available to avoid a large advance release. As a result, the reservoir was allowed to fill early and high releases needed to be made when the true incoming volume would not fit in the space available. In general, however, operations with late forecasts and early forecasts are still able to maintain flows below 160,000 cfs

7.4.2. Magnitude Error Sensitivity Analysis--Performance of Low Forecasts vs. High forecasts

Next, the operational sensitivity to high or low forecasts was tested, assuming 99% refill probabilities. Simulations were created for forecasts that on average predicted a 100-year event and for forecasts which on average predicted a 500-year event. These are the “false-alarm” and “no-alarm” cases discussed in sections 5.3 and 5.4.

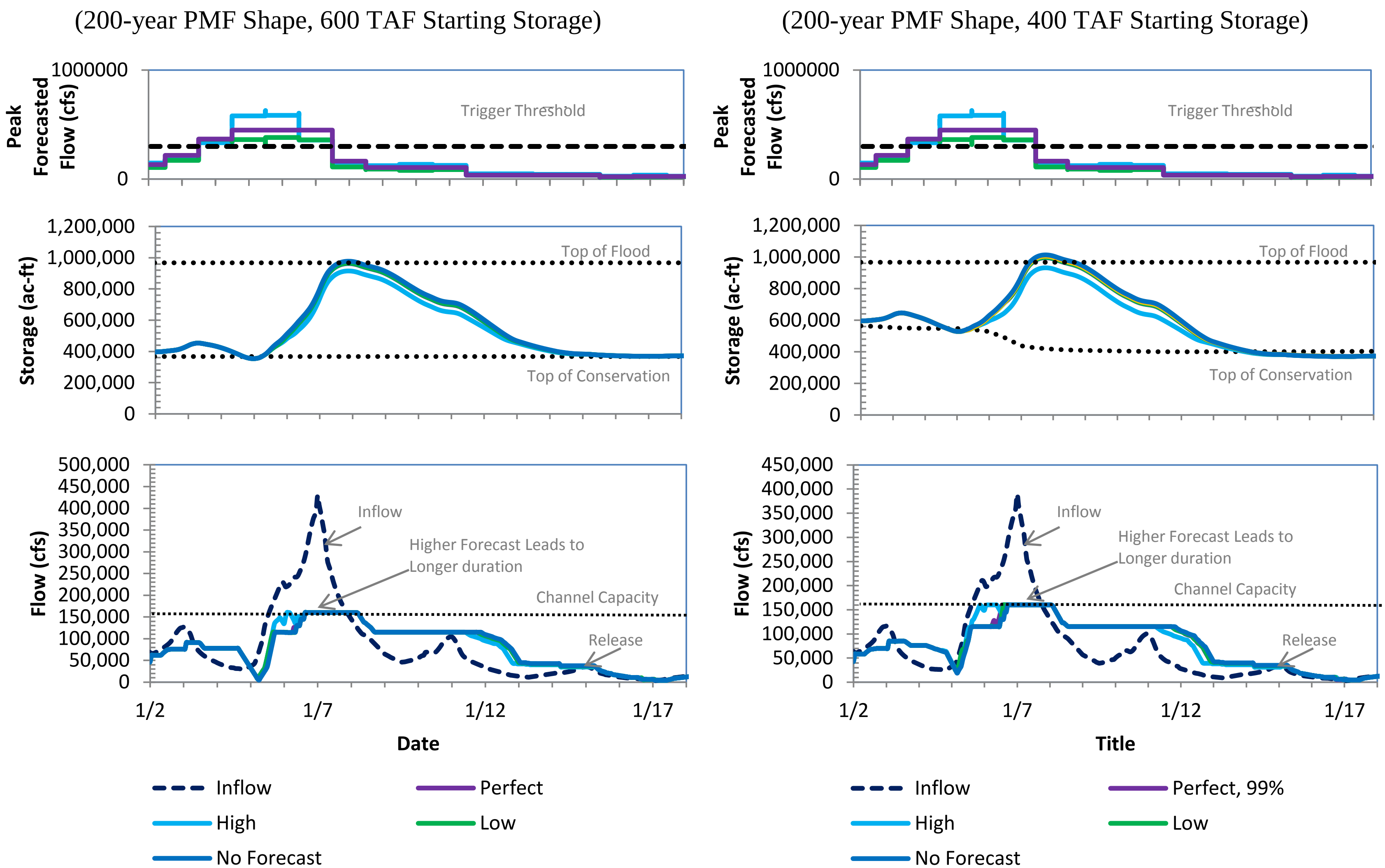

Figure 17(a)

Figure 17b)

Figure 17. 1-in-200 year operations-Sensitivity to Forecast Error for Different Hydrograph Shapes

(200-year SPF Shape, 600 TAF Starting Storage)

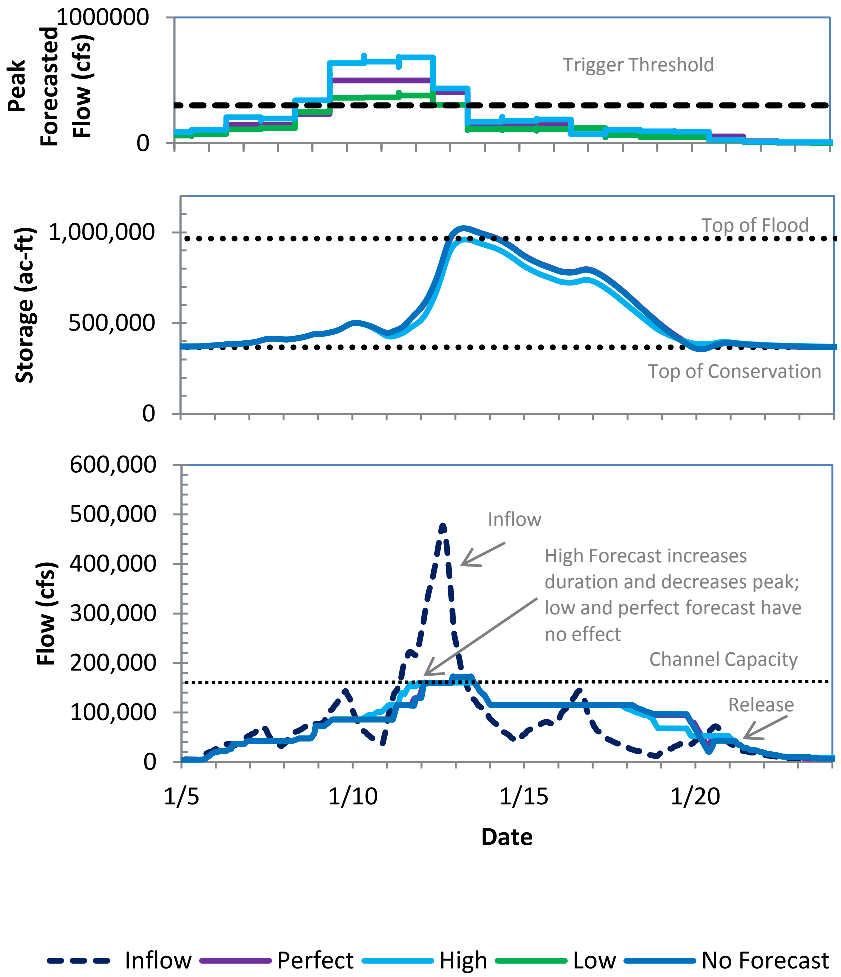

Figure 17 (c)

(200-year SPF Shape, 400 TAF Starting Storage)

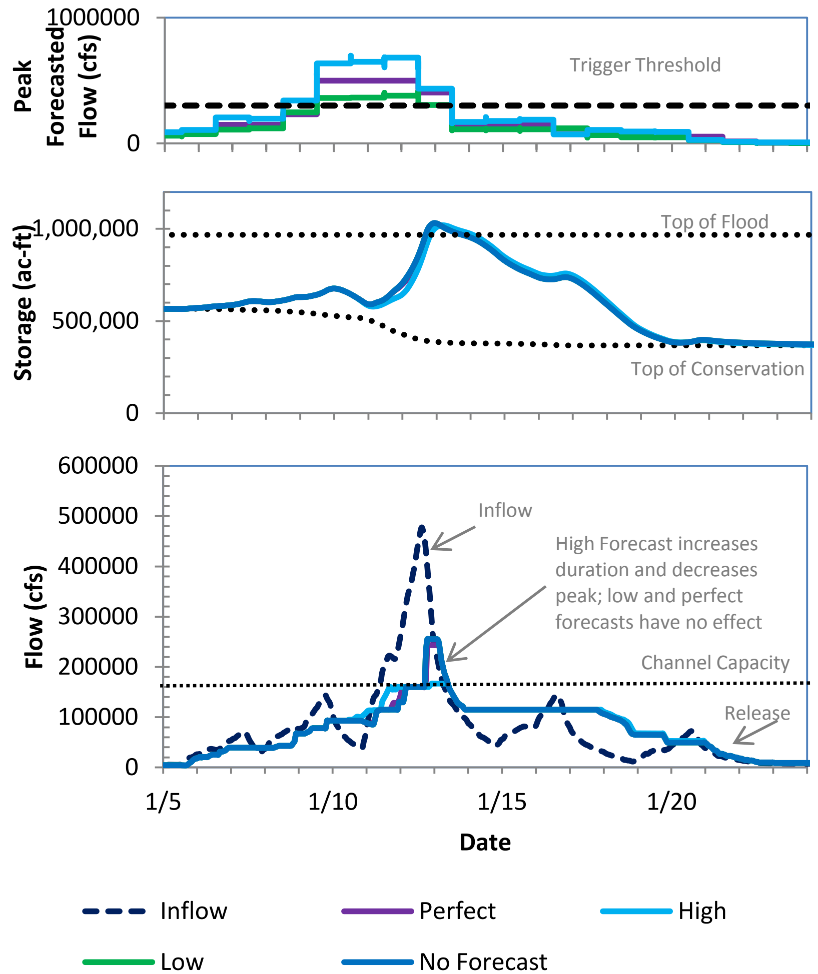

Figure 17 (d)

Figure 17, Continued

(200-year 1955 Shape, 600 TAF Starting Storage)

(200-year 1955 Shape, 400 TAF Starting Storage)

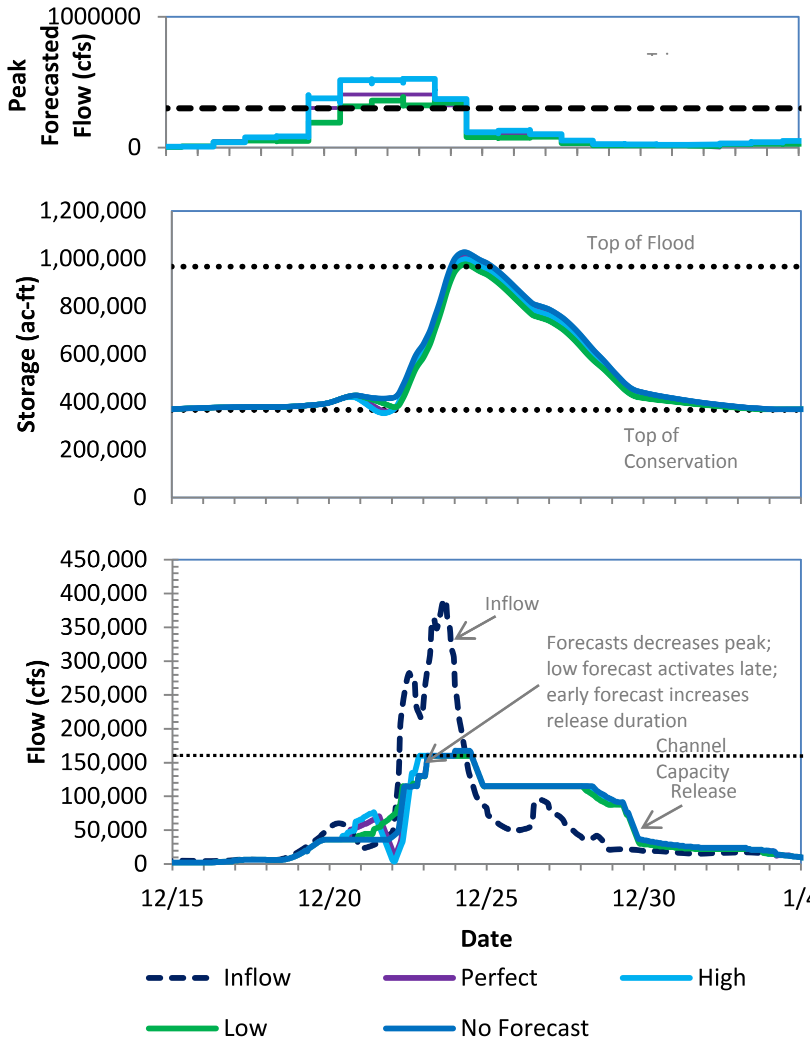

Figure 17 (e)

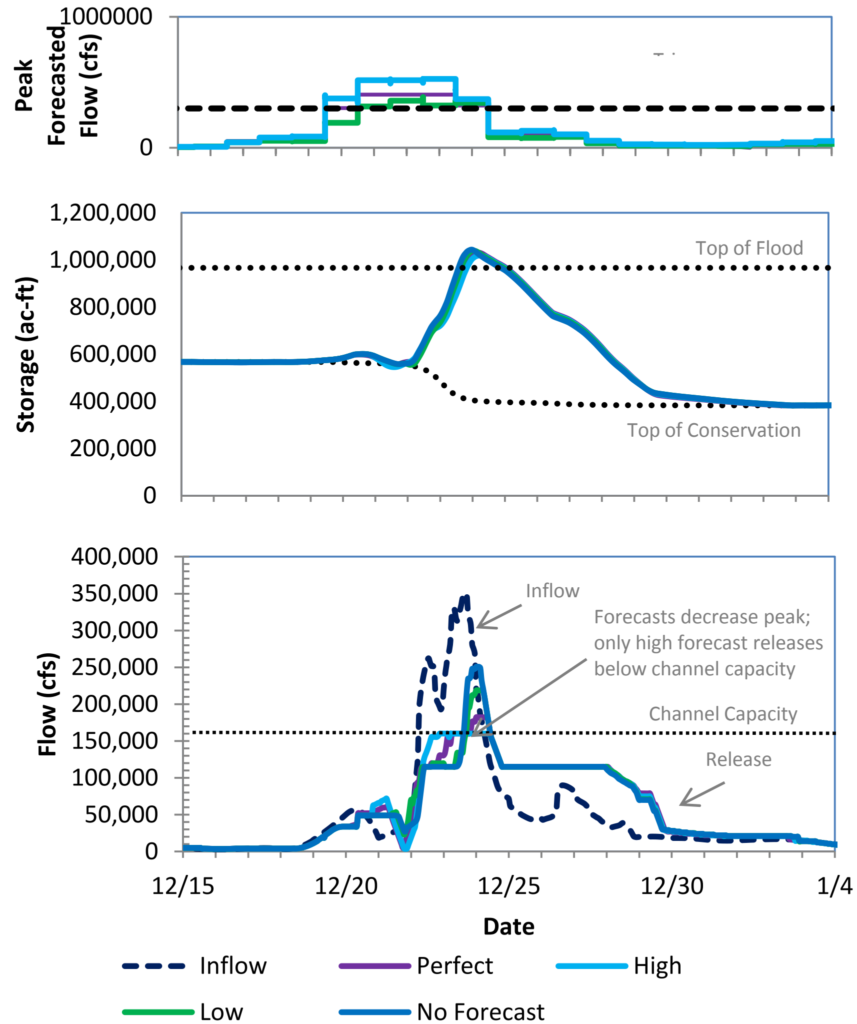

Figure 17 (f)

Figure 17, Continued.

(200-year 1965 Shape, 600 TAF Starting Storage)

(200-year 1965 Shape, 400 TAF Starting Storage)

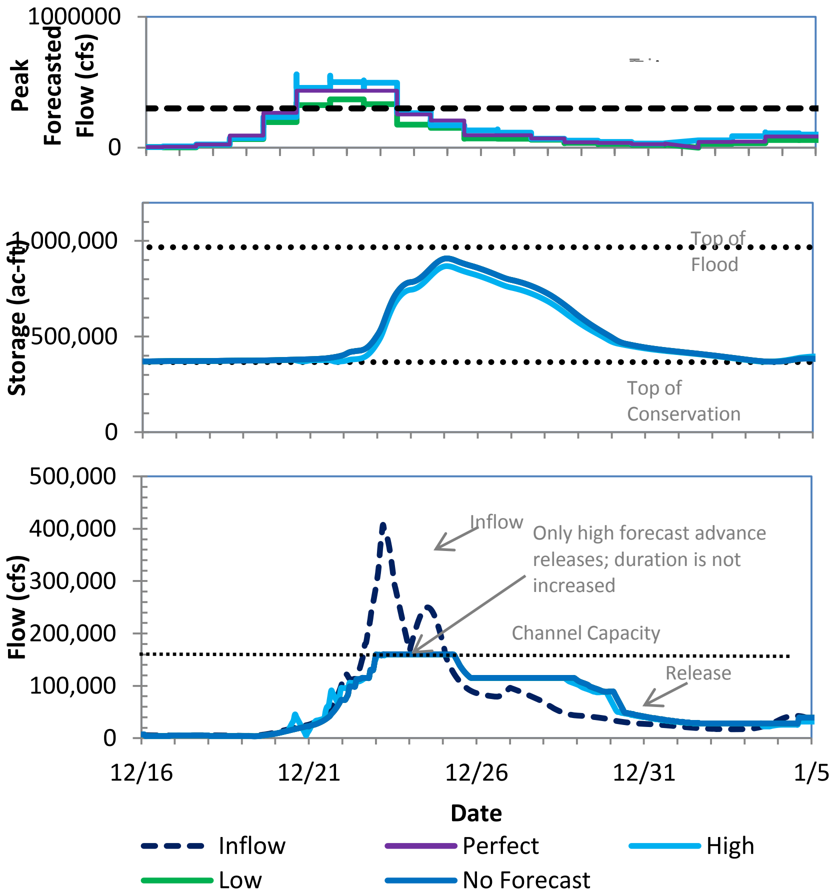

Figure 16(g)

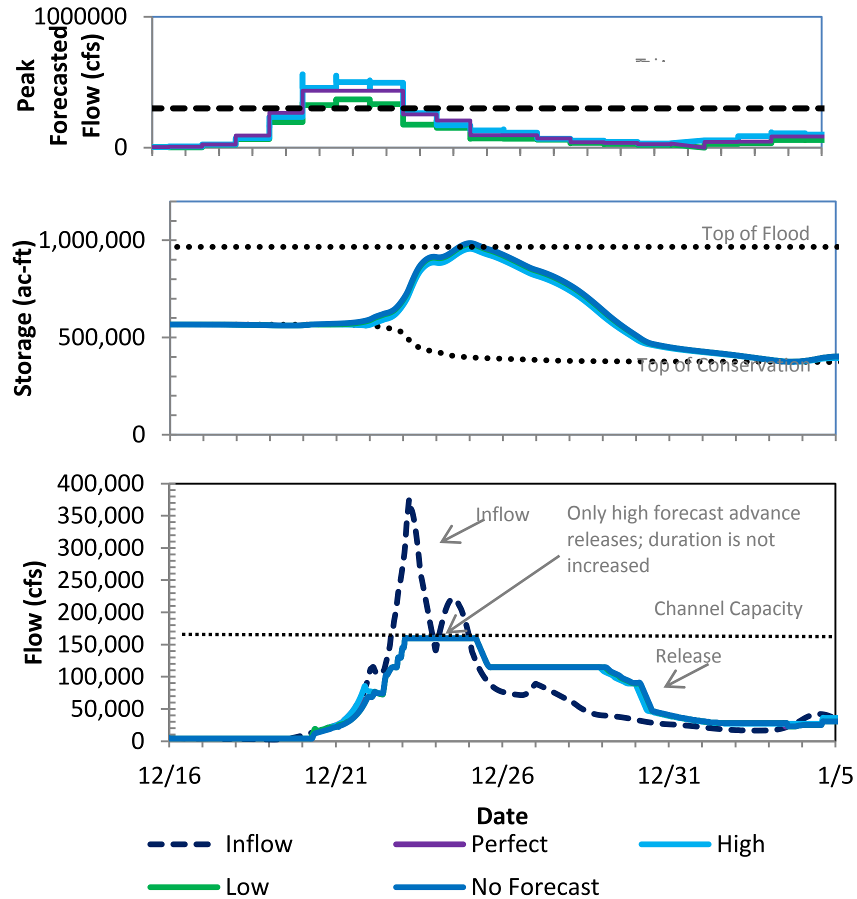

Figure 17 (h)

Figure 17, Continued.

(200-year 1986 Shape, 600 TAF Starting Storage)

(200-year 1986 Shape, 400 TAF Starting Storage)

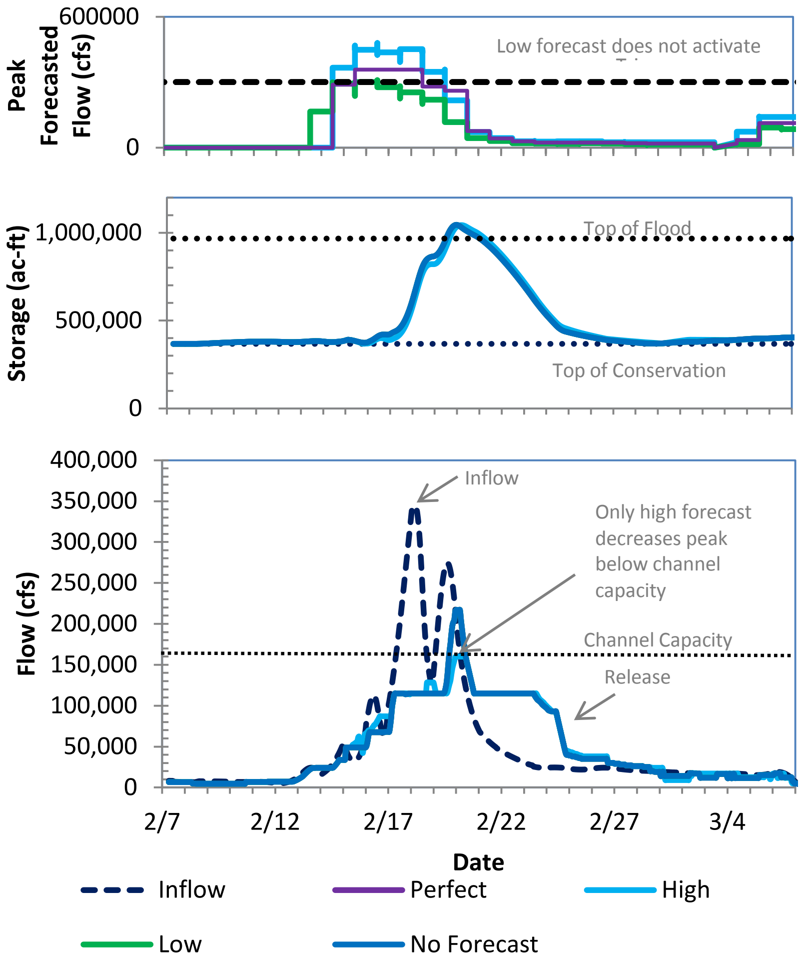

Figure 17 (i)

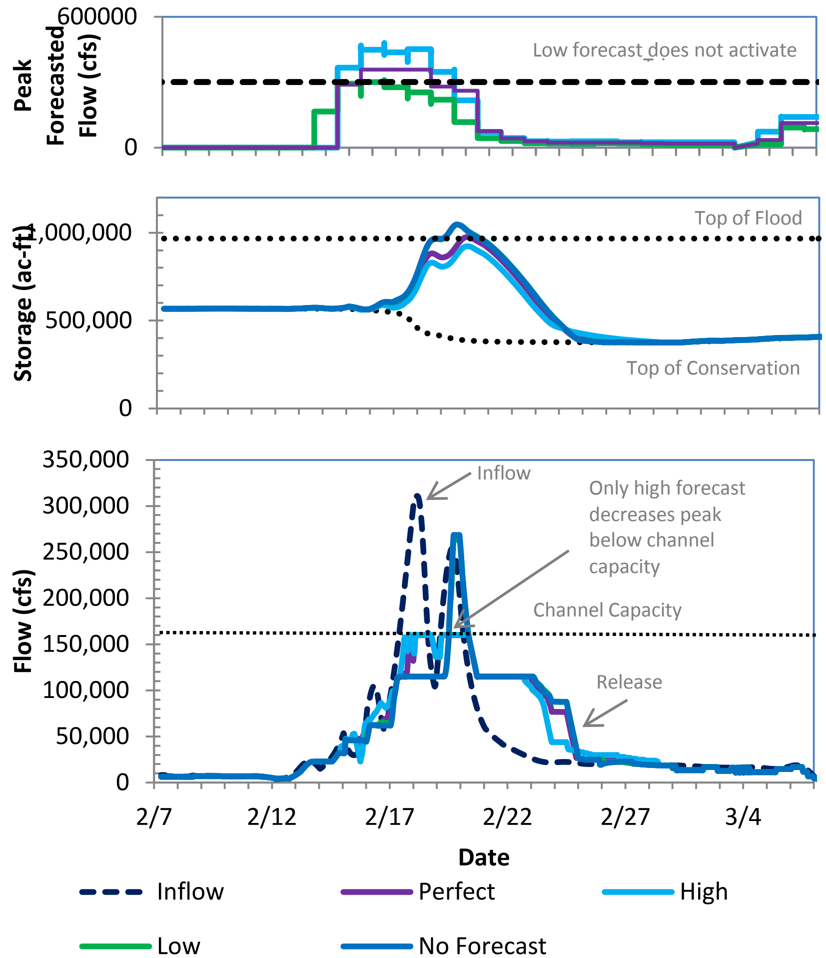

Figure 17 (j)

Figure 17, Continued.

(200-year 1997 Shape, 600 TAF Starting Storage)

(200-year 1997 Shape, 400 TAF Starting Storage)

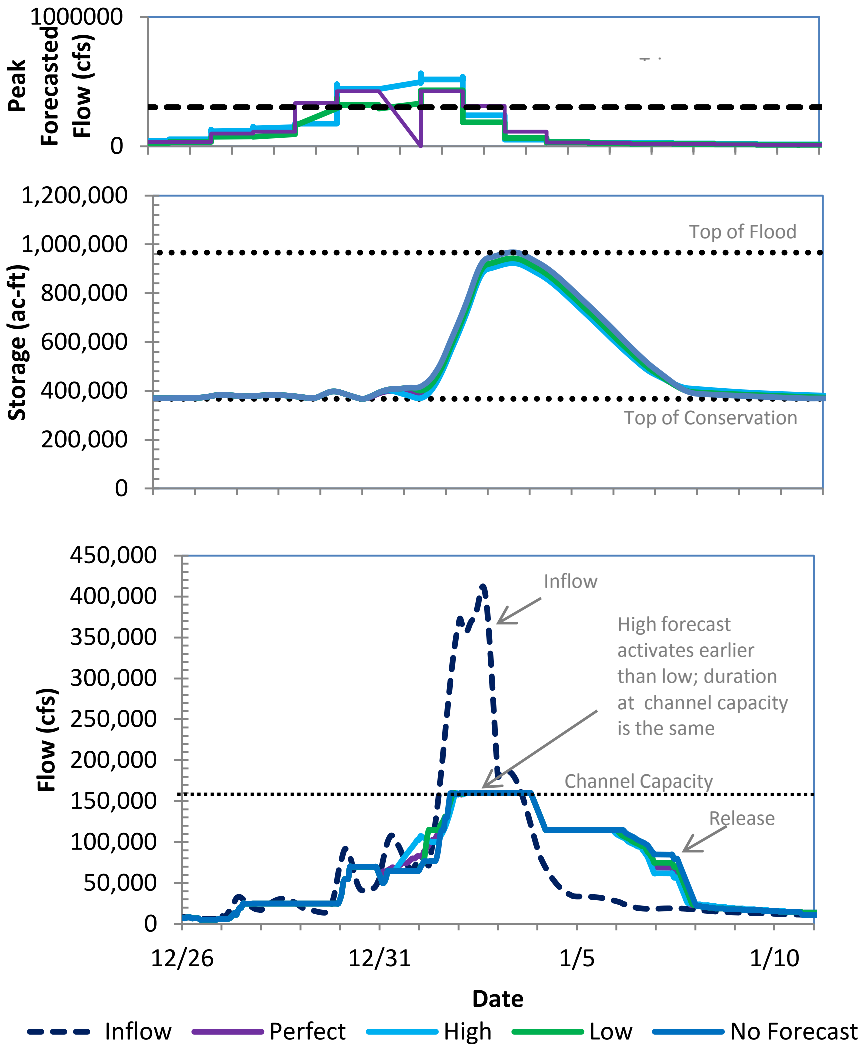

Figure 17 (k)

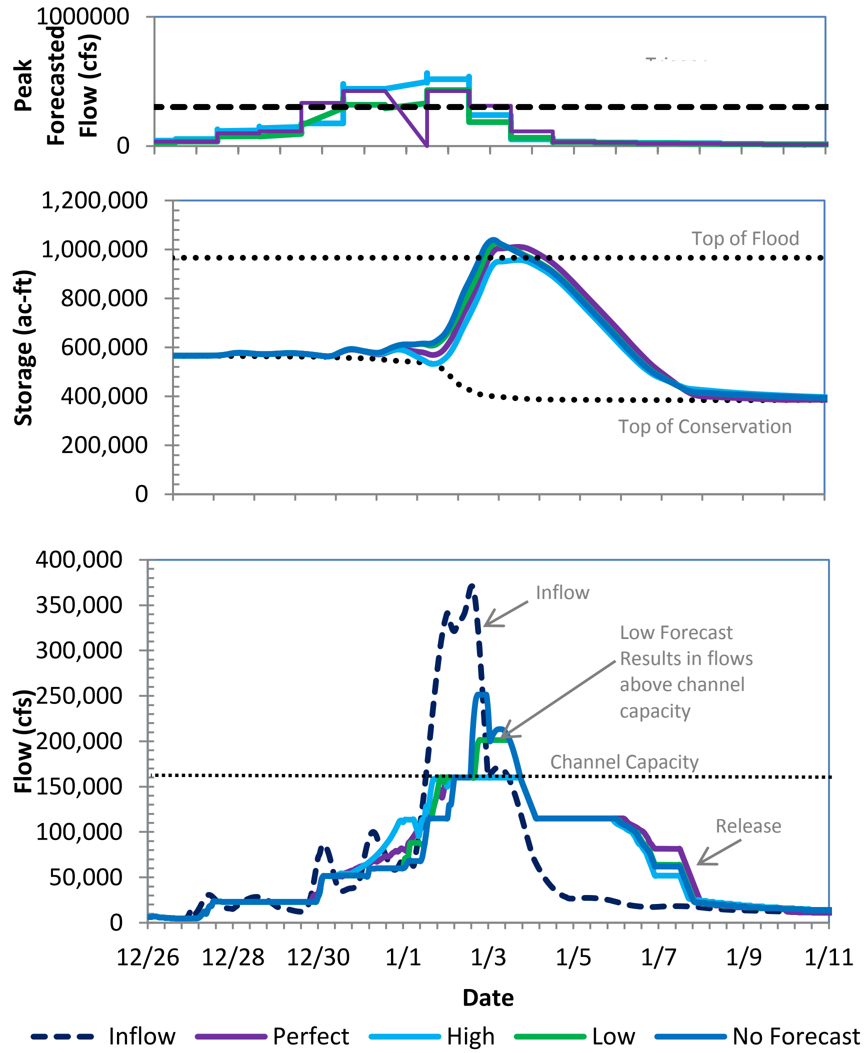

Figure 17 (l)

Figure 17, Continued.

Table 10a 1-in-200 year operations-Sensitivity to Forecast Magnitude Error for Different Hydrograph Shapes**.**

400	PMF	PMF	SPF	SPF	1955	1955	1964	1964	1986	1986	1997	1997
Error	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Peak Storage(ac-ft)	931.8	996.8	1,020	1,031	1,021	1,040	955.9	981.7	923.3	1,047	957.2	1,026
Peak Outflow(cfs)	160	160	**167**	**255**	160	**219**	160	160	160	**263**	160	**201**
Duration >115 kcfs (hr)	71	51	59	47	58	44	66	66	78	33	62	58
Duration >160 kcfs (hr)	0	0	14	17	0	18	0	0	0	20	0	26
Failure Probability	9%	7%	**100%**	**100%**	8%	**100%**	10%	10%	16%	**100%**	9%	**100%**

Table 10b. 1-in-200 year operations-Sensitivity to Forecast Magnitude Error for Different Hydrograph Shapes-Maximum Space in the Flood Pool

600	PMF	PMF	SPF	SPF	1955	1955	1964	1964	1986	1986	1997	1997
Error	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Peak Storage(ac-ft)	915.6	963.7	961.5	1023	996.9	975.2	868.2	908.2	1,043	1,044	923.4	942.1
Peak Outflow(cfs)	160	160	160	**173**	160	160	160	160	160	**217**	160	160
Duration >115 kcfs (hr)	73	56	64	53	56	55	72	72	39	32	61	64
Duration >160 kcfs (hr)	0	0	0	16	0	0	0	0	0	18	0	0
Failure Probability	8%	8%	7%	**100%**	8%	7%	10%	10%	5%	**100%**	8%	9%

For floods based on 1997, 1955, and 1986 shapes, for the cases where the reservoir started with 400 TAF flood storage, the low forecast resulted in peak outflows greater than 160,000; nonetheless, these peaks were less than the operations without forecasts. The releases based on low forecasts were primarily constrained by the fact that the incoming volume was predicted to be low, and so releases were not typically limited by the guide curve constraint.

High forecasts (500-year forecasts for a 200-year event) never resulted in flows above 160,000, even for challenging events such as 1986 and 1955. For the 1986 shape with both the 600 TAF case and the 400 TAF case, the high forecasts even reduced the peaks below 160,000. High forecasts or "false alarms" generally allowed increased releases earlier on in the flood. The guide curve constraint was beneficial in the false alarm case because it prevented the rule from releasing too much water too quickly when the forecasts were higher than the actual inflow.

7.5. Perfect Forecasts

Theoretically, the best case for forecasts would be that all the forecasts exactly predict the timing and magnitude of the incoming event, and the rules operate based on the assumption that the forecasts were perfect with no uncertainty. To test whether this was true, a simulation was run using perfect forecasts and varying refill probabilities. Of these probabilities, one (the 50% refill probability) represents the rule which assumes *no uncertainty* and is expected to operate the least conservatively.

(200-year PMF Shape, 600 TAF Starting Storage)

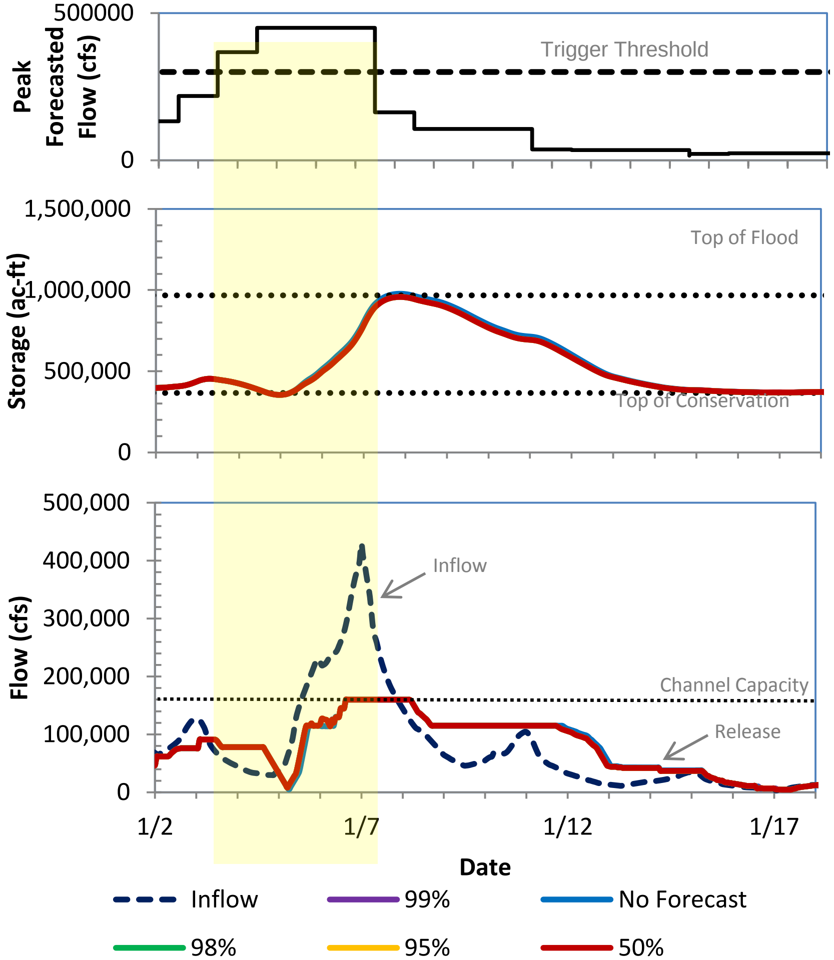

Figure 18a

(200-year PMF Shape, 400 TAF Starting Storage)

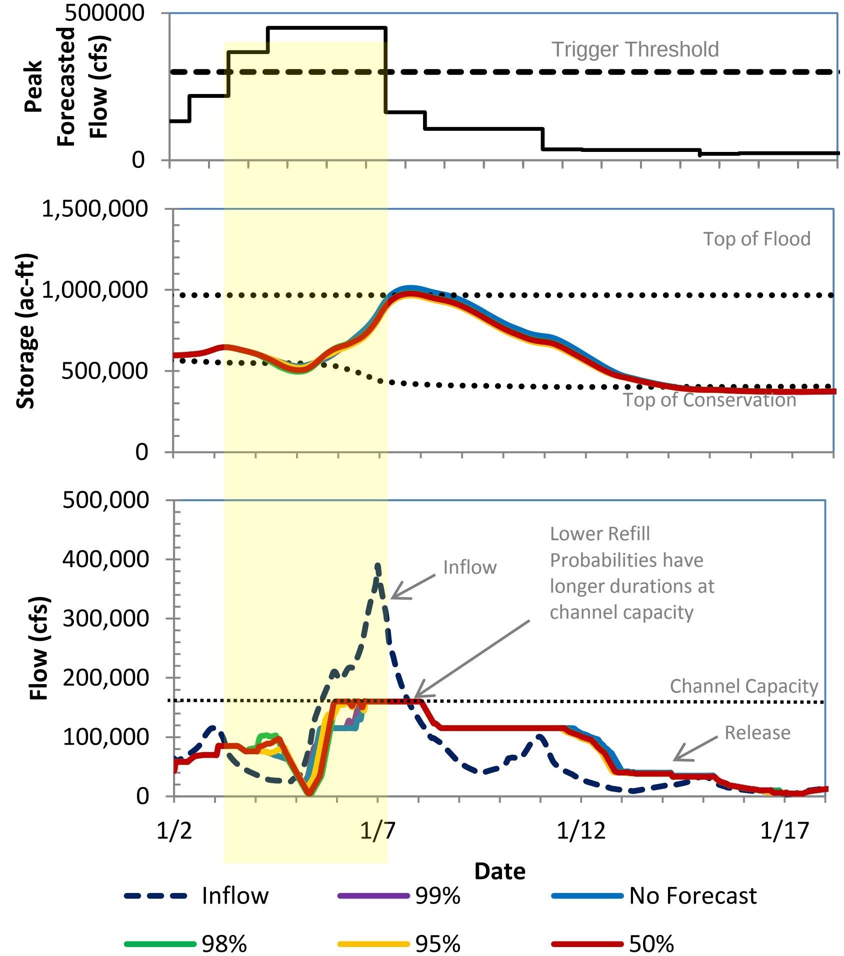

Figure 18b

Figure 18 1-in-200 year operations-Sensitivity to Refill Probability

(200-year SPF Shape, 600 TAF Starting Storage)

(200-year SPF Shape, 400 TAF Starting Storage)

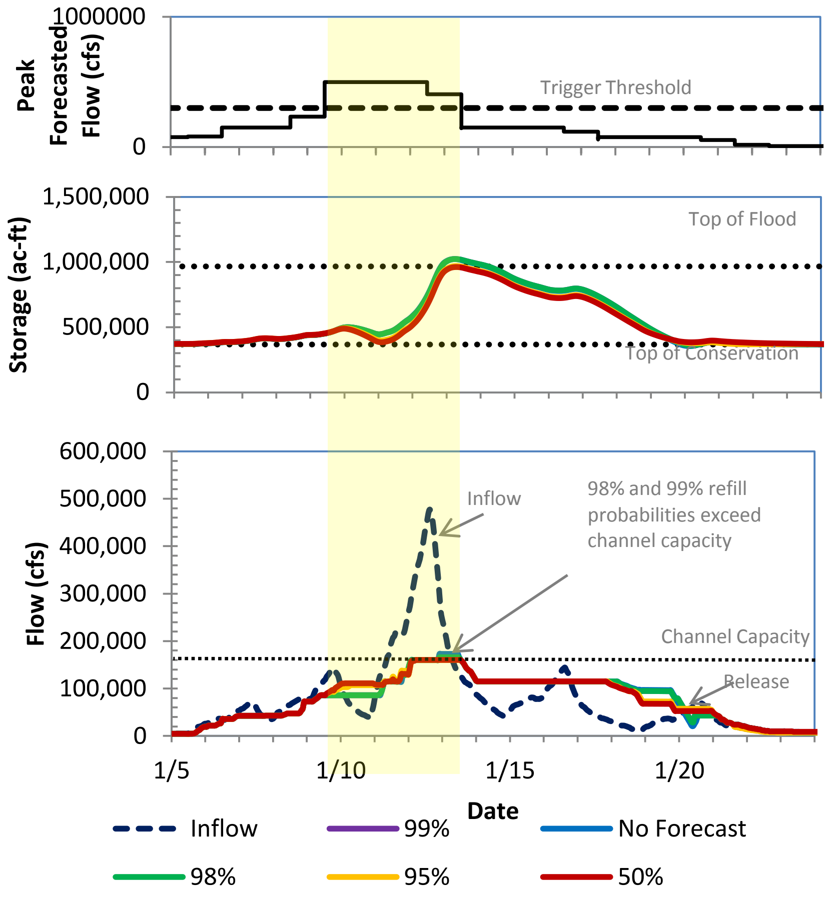

Figure 18c

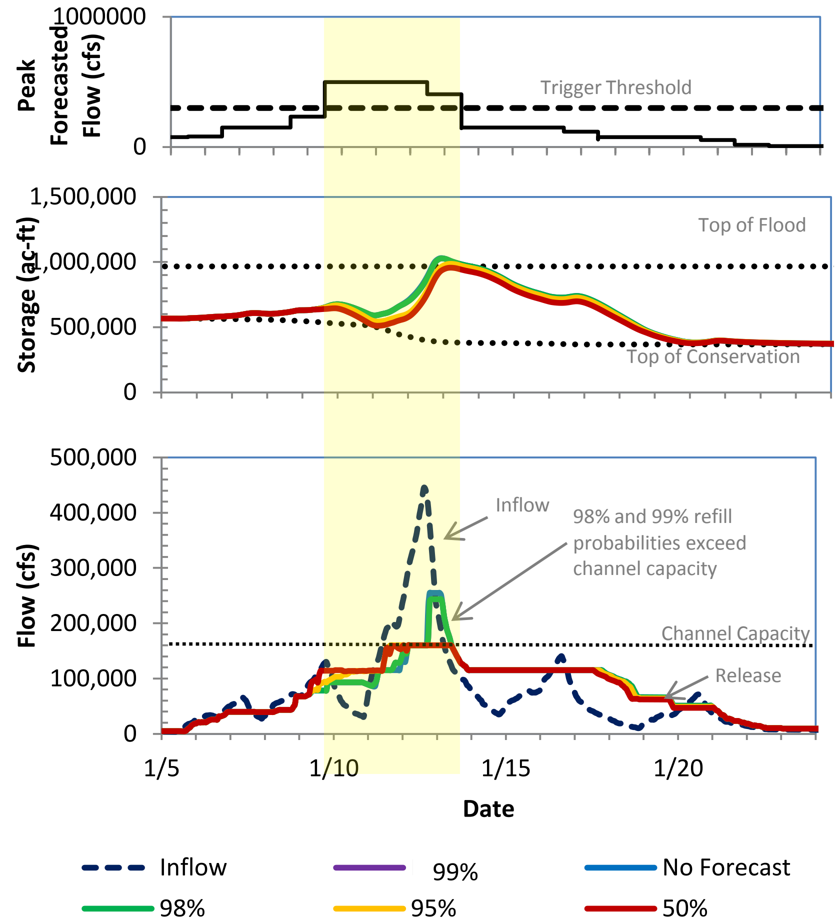

Figure 18d

Figure 18, Continued.

(200-year 1955 Shape, 600 TAF Starting Storage)

(200-year 1955 Shape, 400 TAF Starting Storage)

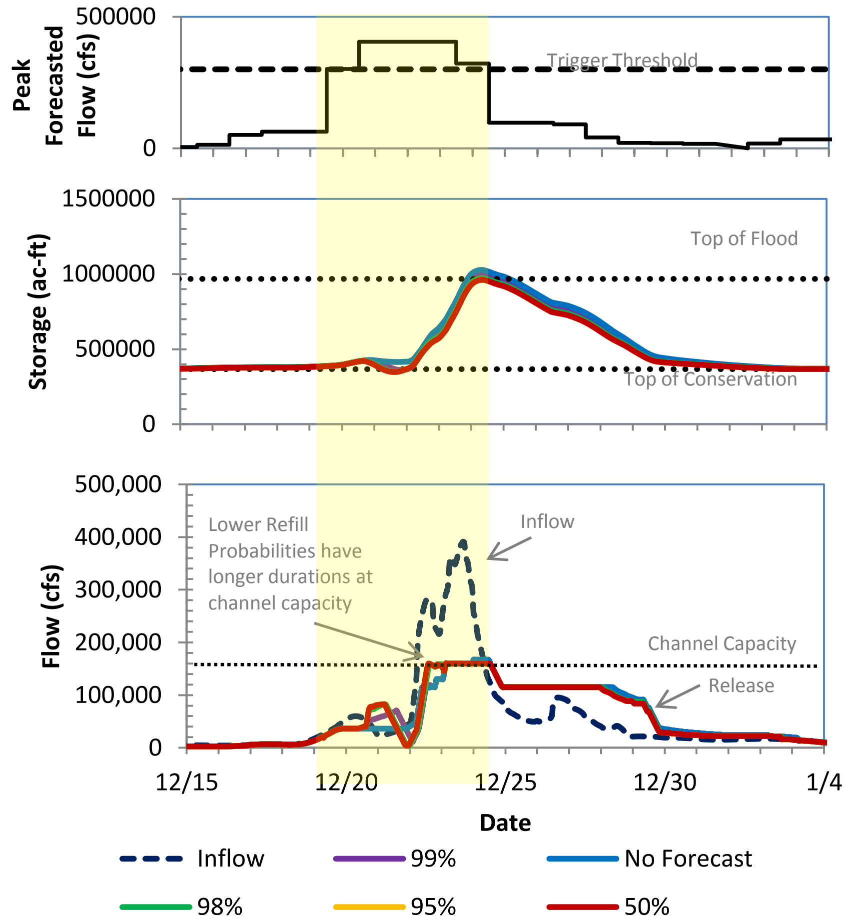

Figure 18e

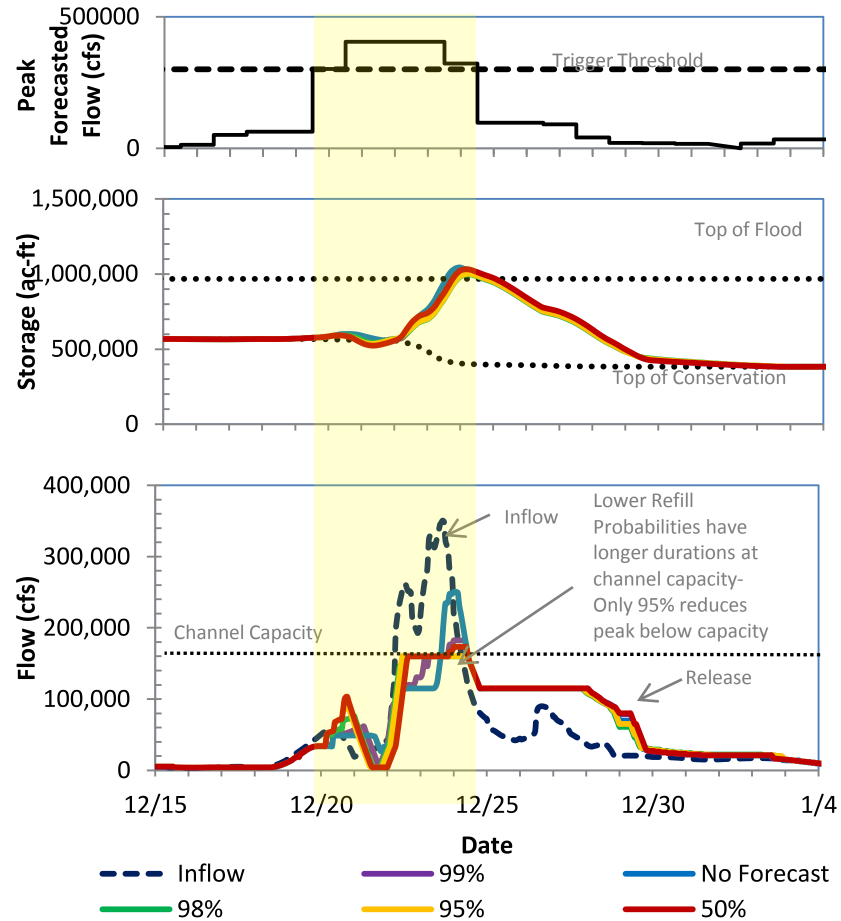

Figure 18f

Figure 18, Continued.

(200-year 1964 Shape, 600 TAF Starting Storage)

(200-year 1964 Shape, 400 TAF Starting Storage)

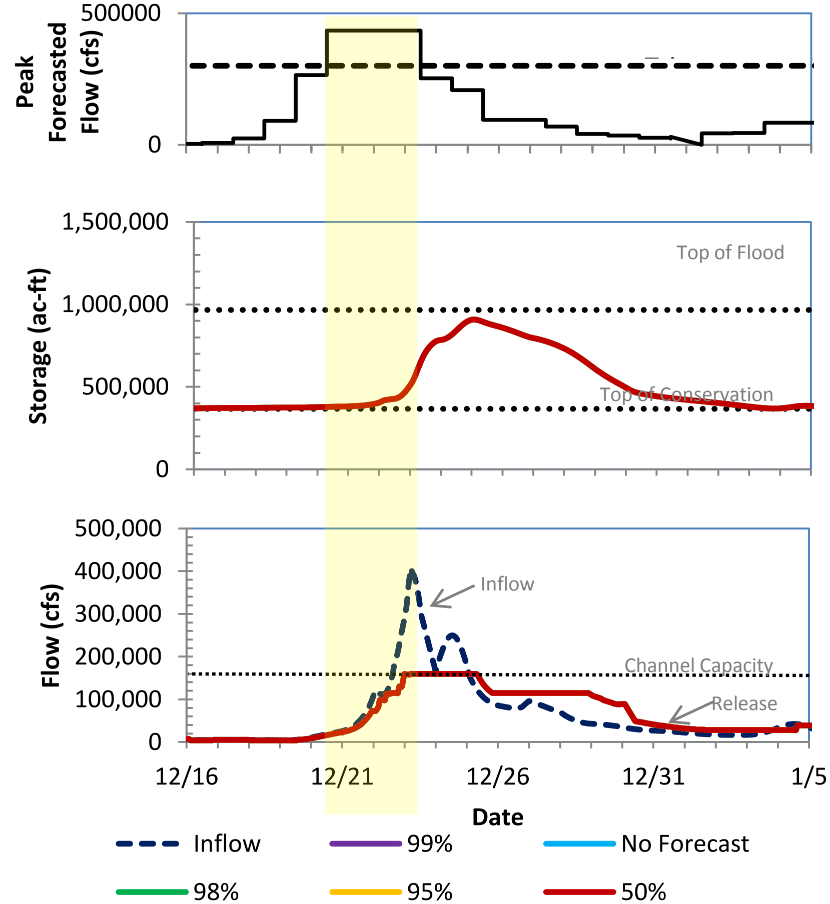

Figure 18g

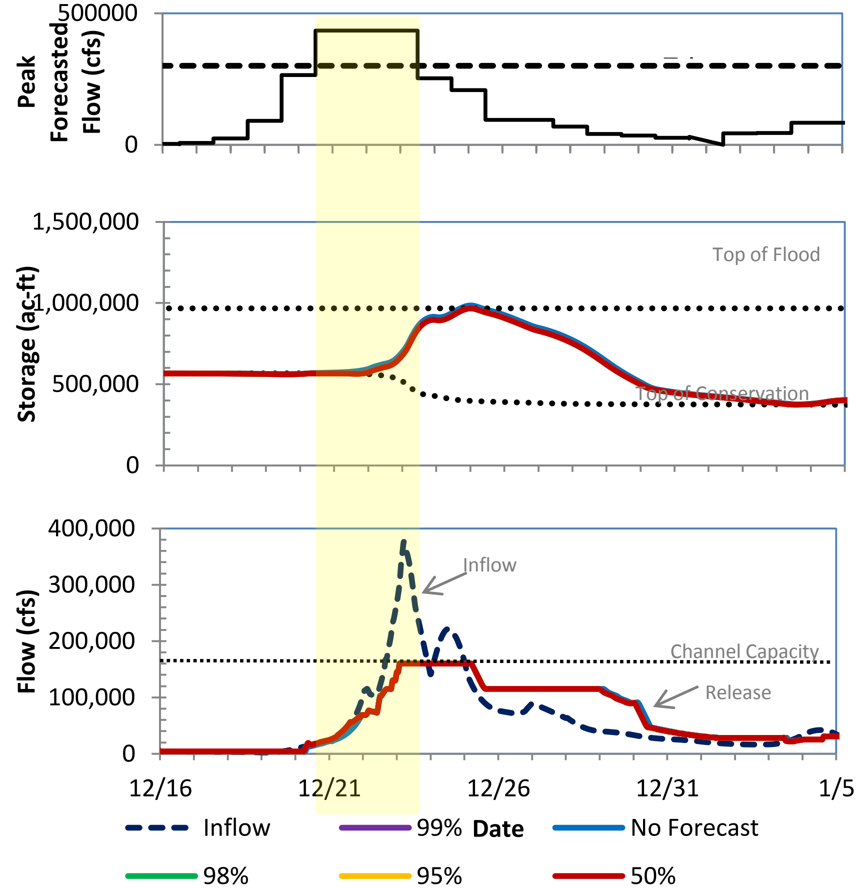

Figure 18h

Figure 18, Continued.

(200-year 1986 Shape, 600 TAF Starting Storage)

(200-year 1986 Shape, 400 TAF Starting Storage)

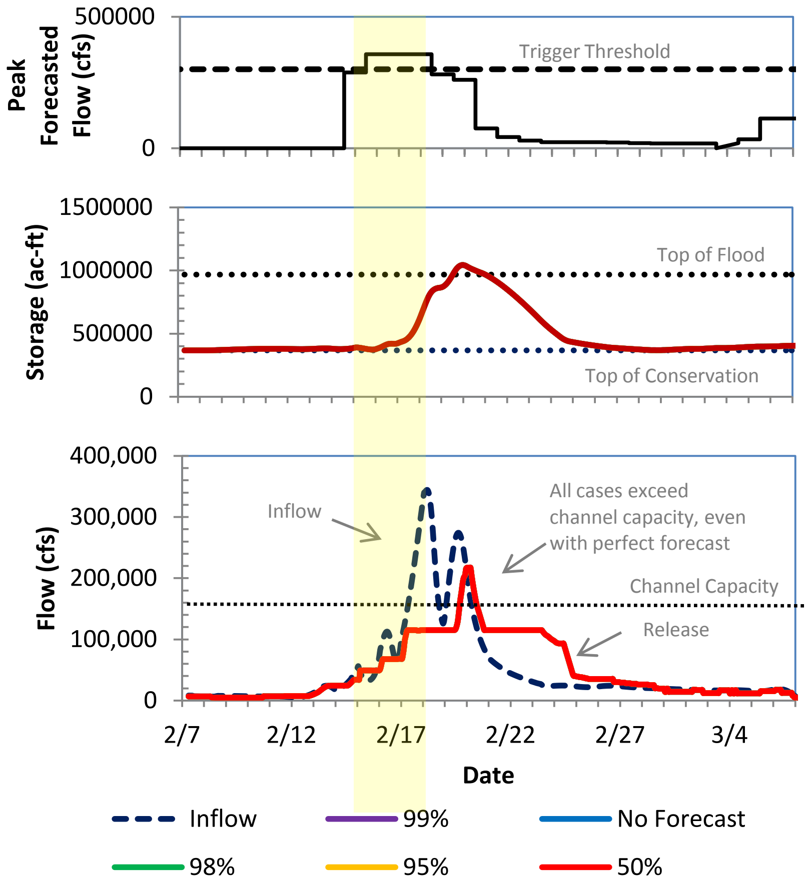

Figure 18i

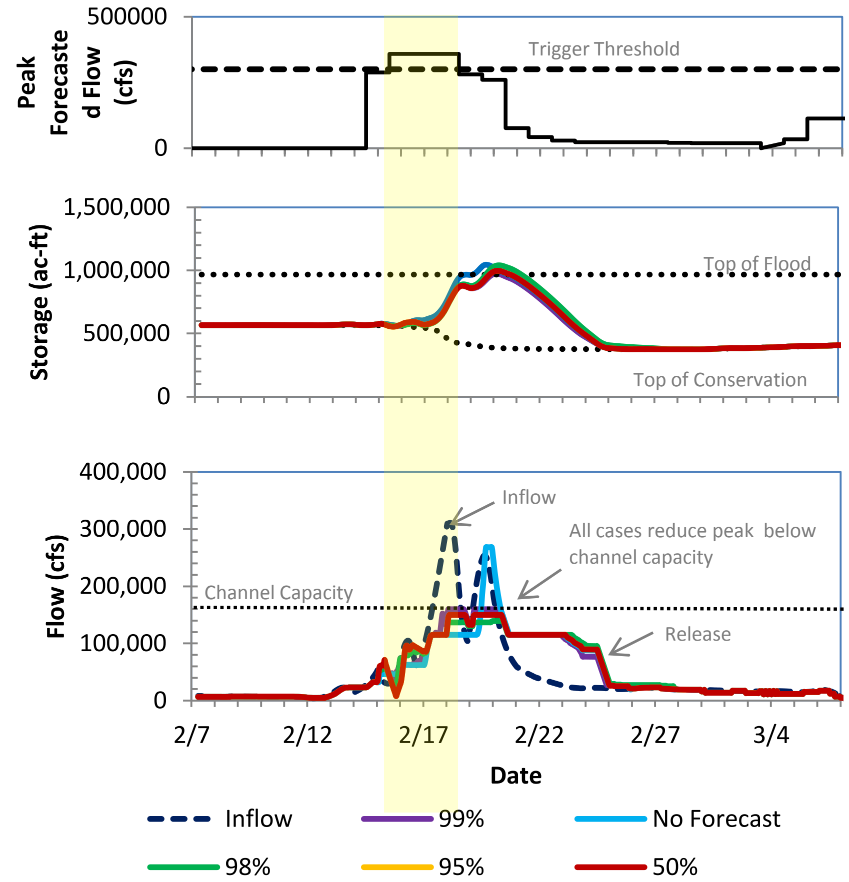

Figure 18j

Figure 18, Continued.

(200-year 1997 Shape, 600 TAF Starting Storage)

(200-year 1997 Shape, 400 TAF Starting Storage)

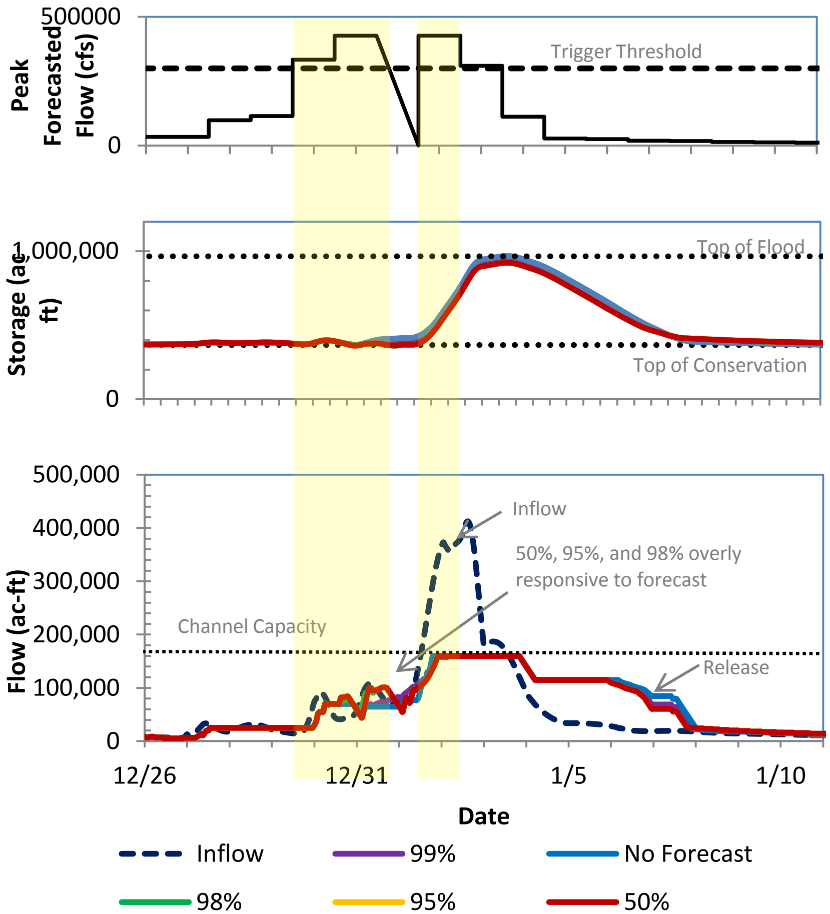

Figure 18k

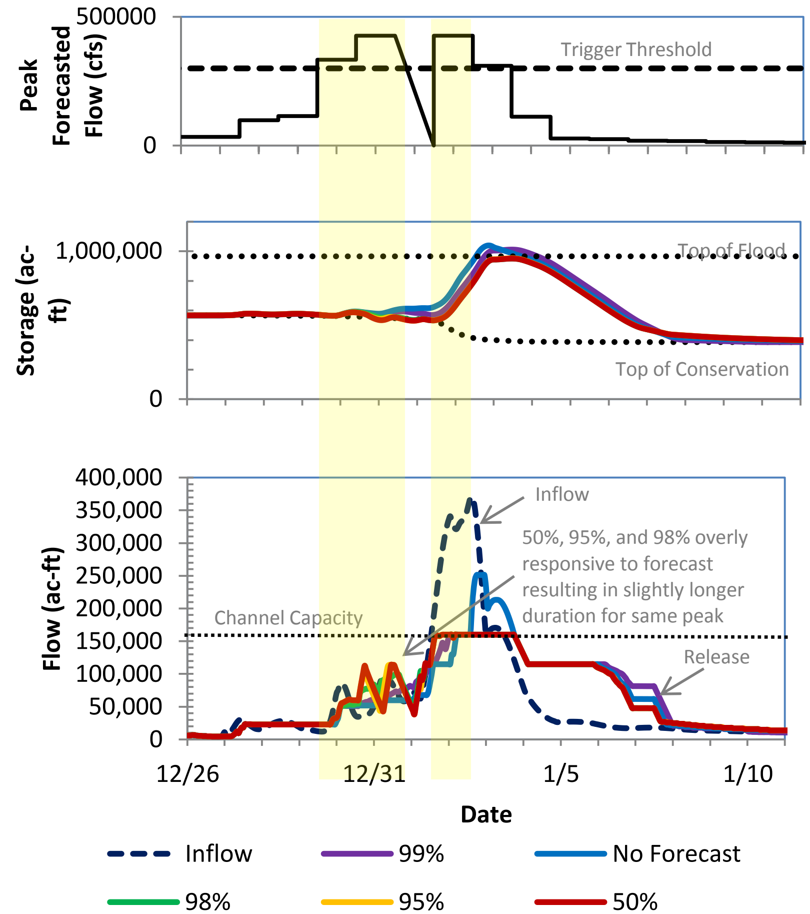

Figure 18l

Figure 18, Continued.

Operations with perfect forecasts and 99% refill probability reduced the peak below 160,000 for all cases except two: 1986 shape with maximum 600 TAF storage space in flood pool, and 1955 shape with minimum 400 TAF storage space in the flood pool.

For the 1986 shape, starting with the maximum 600 TAF storage space at Folsom, forecast releases did not reduce the peak. For the 1986 shape starting with the minimum 400 TAF storage space at Folsom, forecast releases reduced the peak to 160,000 or below. Since the reservoir started with more flood space available at the time the second peak appeared in the forecast, the advance release specified by the rule was either zero or too small to affect operations.

When the reservoir started with greater water storage in the flood pool, less flood control space was available, resulting in increased advance release and decreased peak. The 1986 case with perfect forecasts demonstrated how a low starting pool elevation can be challenging for advance release, even with a high forecasted inflow. Low starting elevations mean that space available is high; the high space available coupled with the long time to the peak leads to a low advance release, if any advance release is made at all.

Conversely, compared to when it started with the maximum 600 TAF of storage space in Folsom, the 1955 shape performed poorly with forecast rules when starting with the minimum 400 TAF of storage space in Folsom. In this case, there was simply not enough room in the flood pool with the higher water storage to store the incoming event, even with advance release.

7.6. Comparison of Proposed Rule and other Rules

The proposed rule was compared with the rule from MBK using the imperfect on-time forecast (Appendix B). The proposed rule is triggered at 300,000 cfs forecasted inflow, and evaluates the forecast to determine the necessary release to avoid surcharge. The MBK rule is active when the water enters the flood pool regardless of the forecast; it modifies the accelerated transition to determine a release to maximize storage in flood pool, and it modifies the smoothing routine to determine the necessary release to evacuate the flood pool when flood threats are not imminent. The MBK rule species releases in increments; the proposed rule specifies a continuous range of values. Another important difference between the rules is that the proposed rule releases no more water than is 99% likely to be recovered, and the MBK rule *does not* incorporate uncertainty. Results are plotted in Figure 19(a) through Figure 19 (l), below.

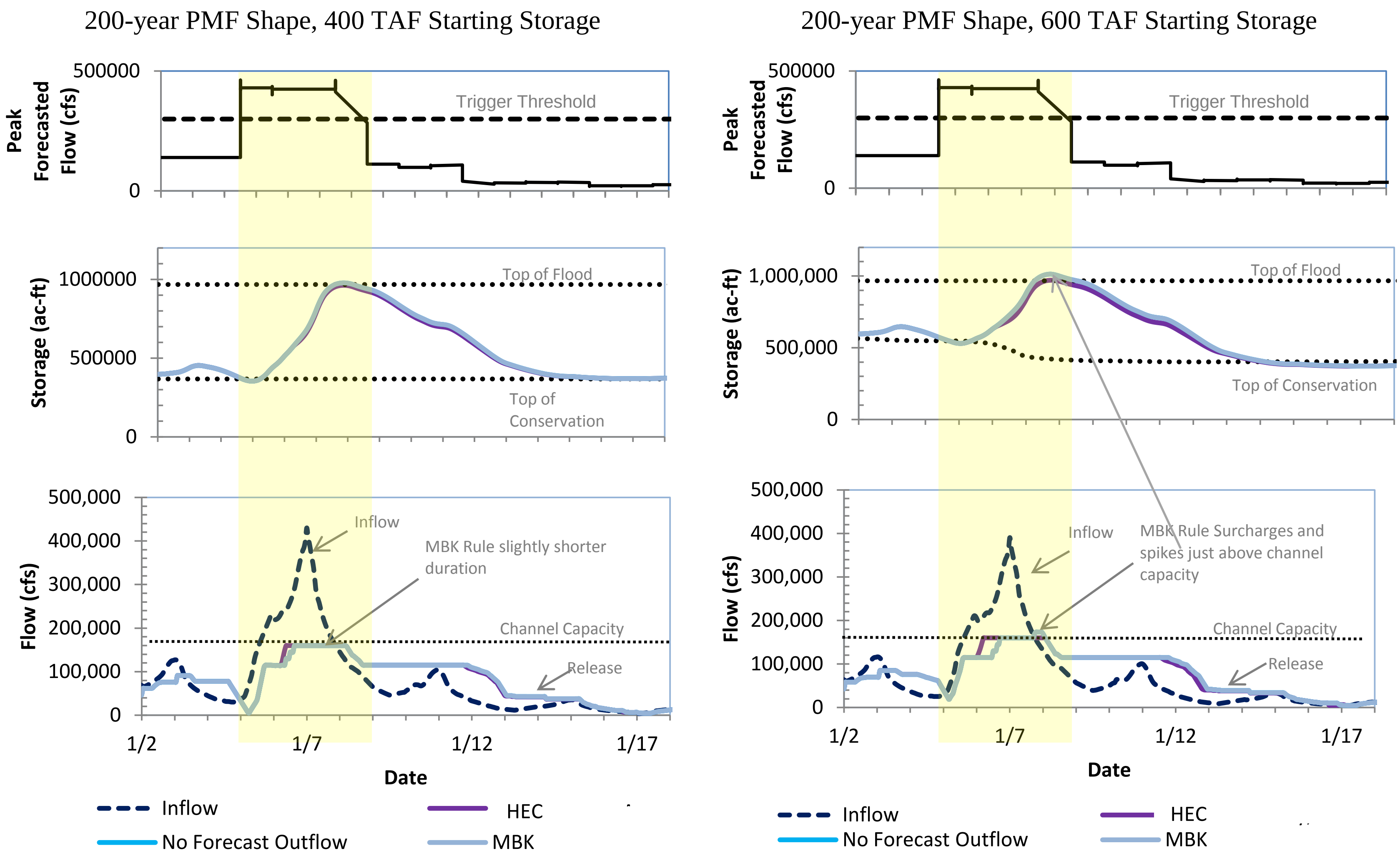

Figure 19(a)

Figure 19(b)

Figure 19. 1-in-200 Year Event. Comparison of HEC and MBK Rules

200-year SPF Shape, 400 TAF Starting Storage

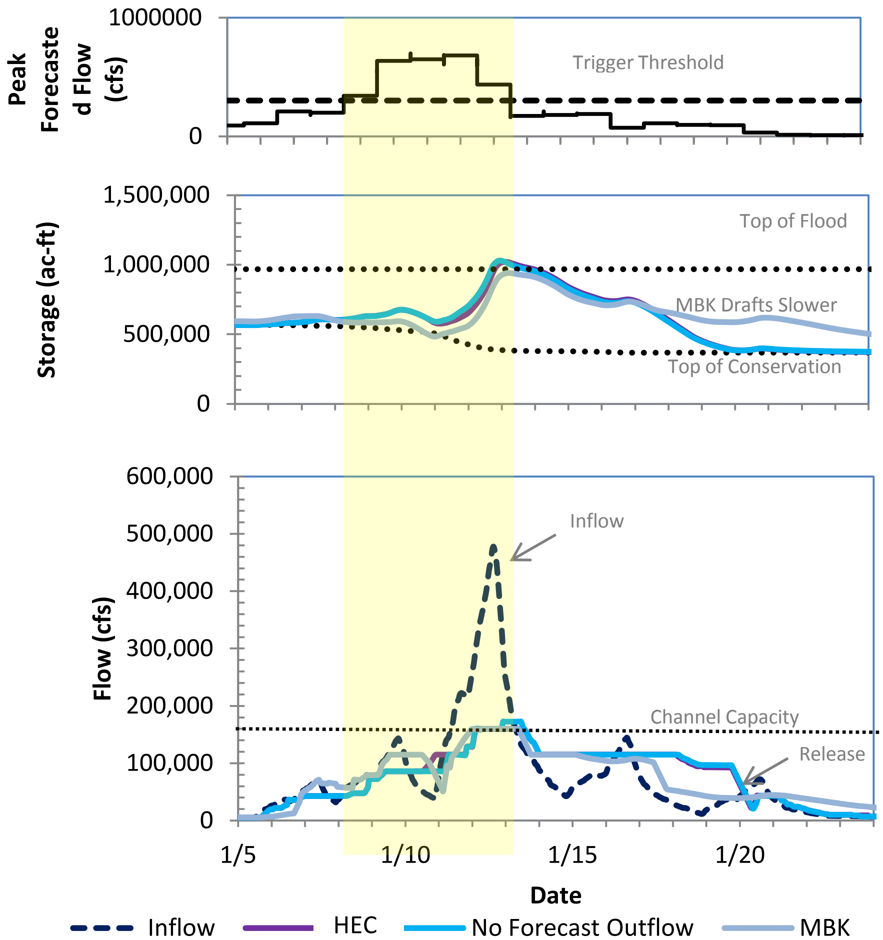

Figure 19(c)

200-year SPF Shape, 600 TAF Starting Storage

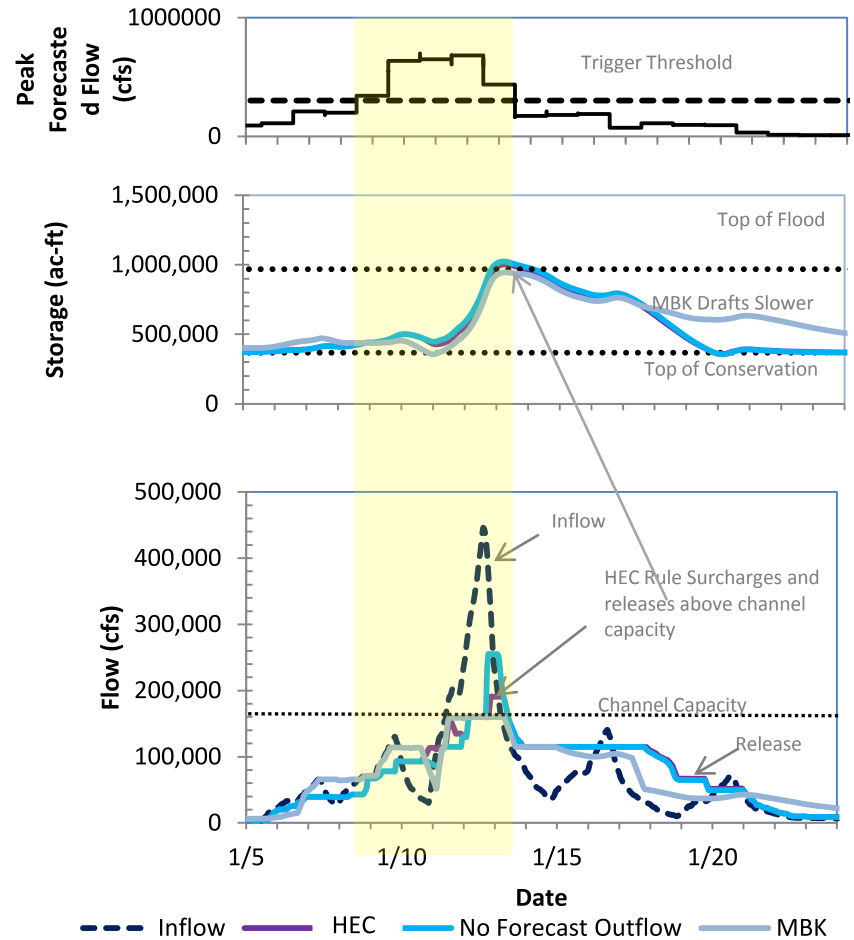

Figure 19(d)

Figure 19, Continued

200-year 1955 Shape, 400 TAF Starting Storage

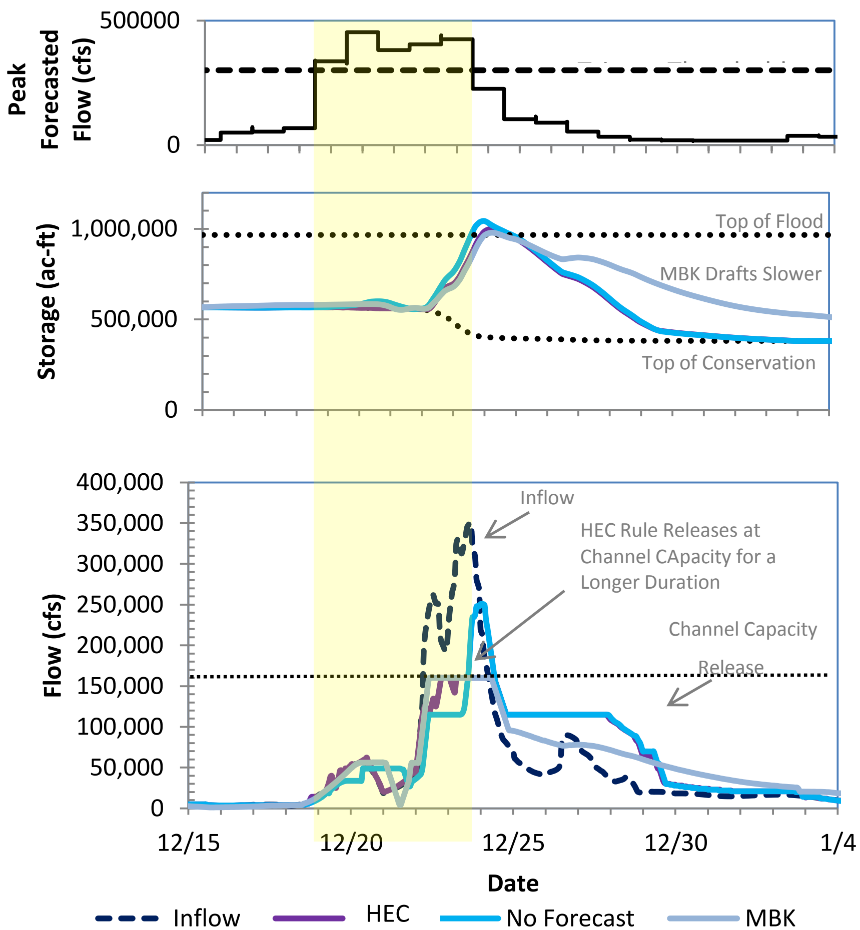

Figure 19(e)

200-year 1955 Shape, 600 TAF Starting Storage

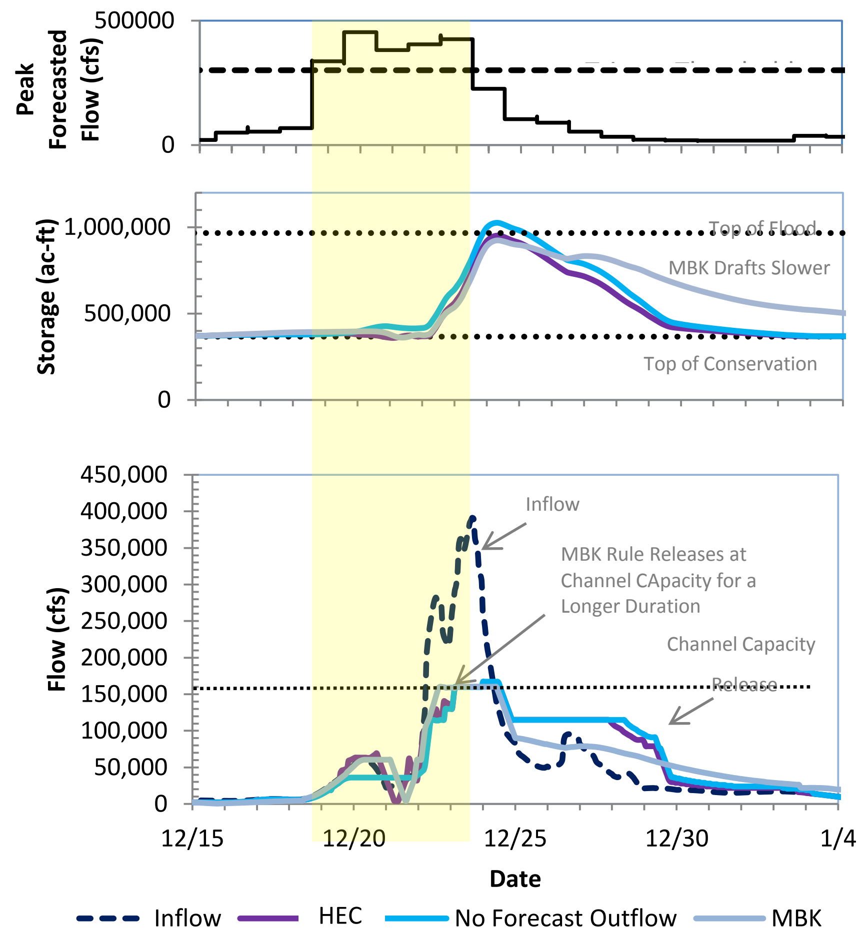

Figure 19(f)

Figure 19, Continued

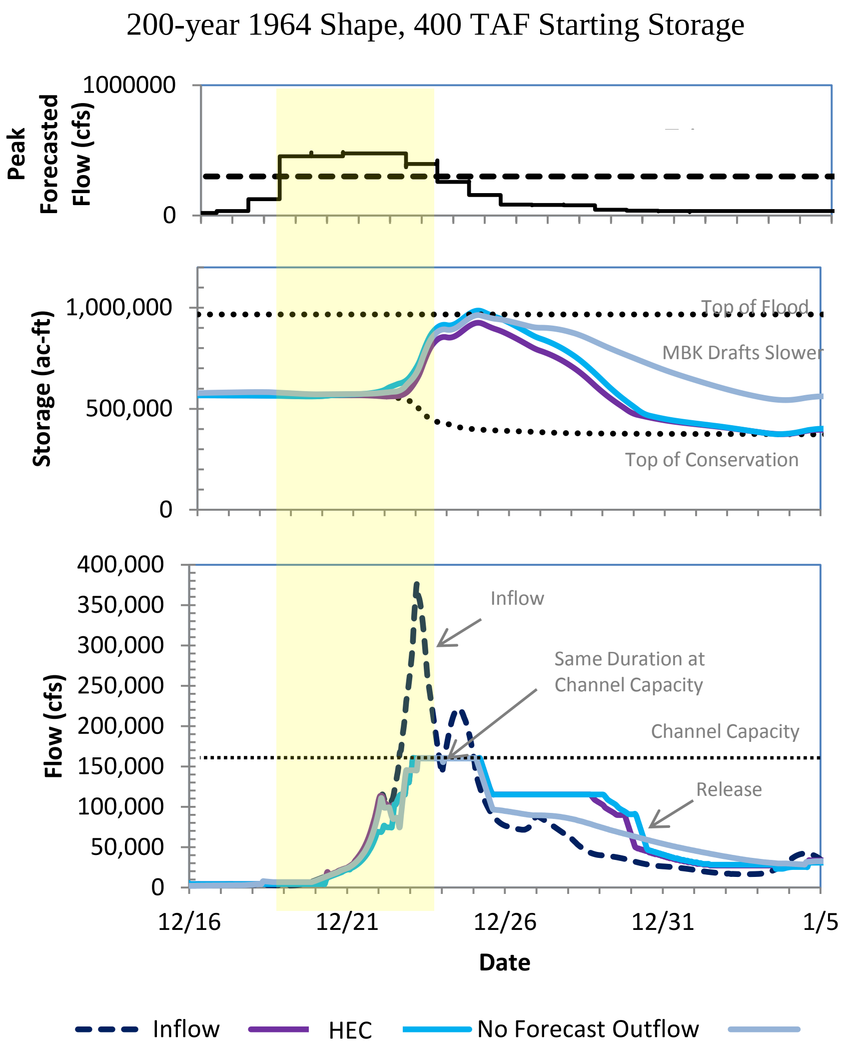

Figure 19(g)

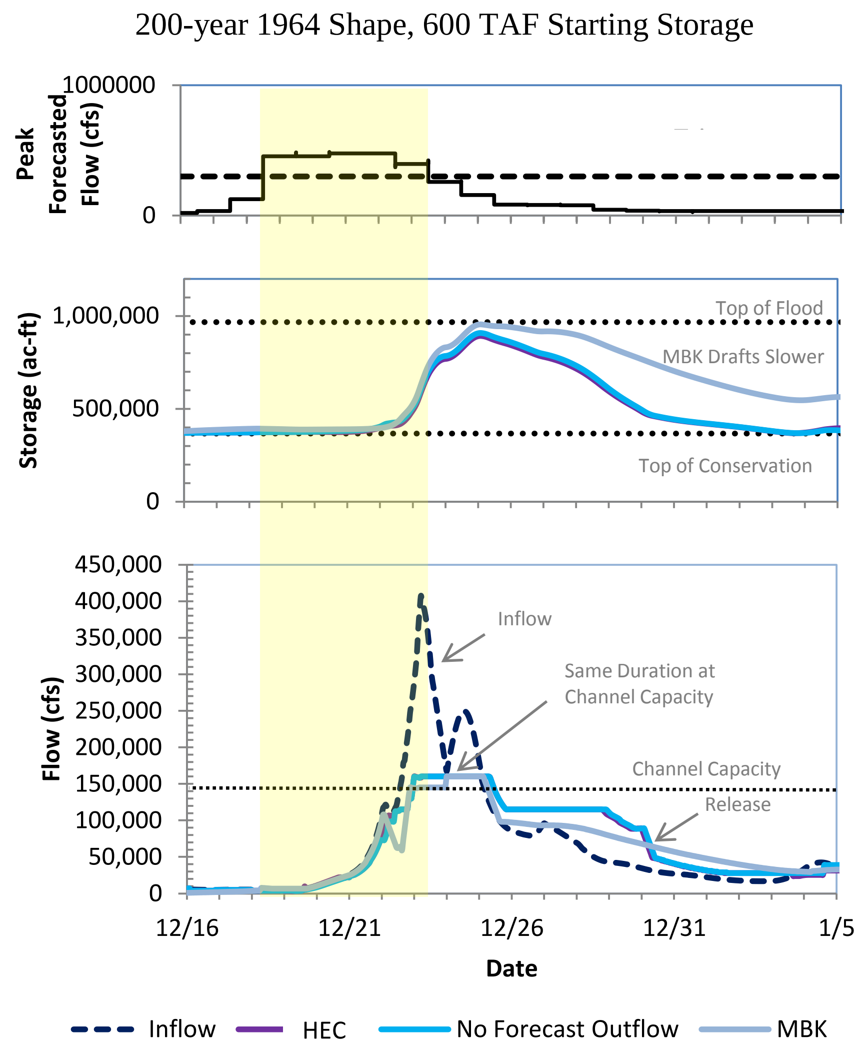

Figure 19 (h)

Figure 19, Continued

200-year 1986 Shape, 400 TAF Starting Storage

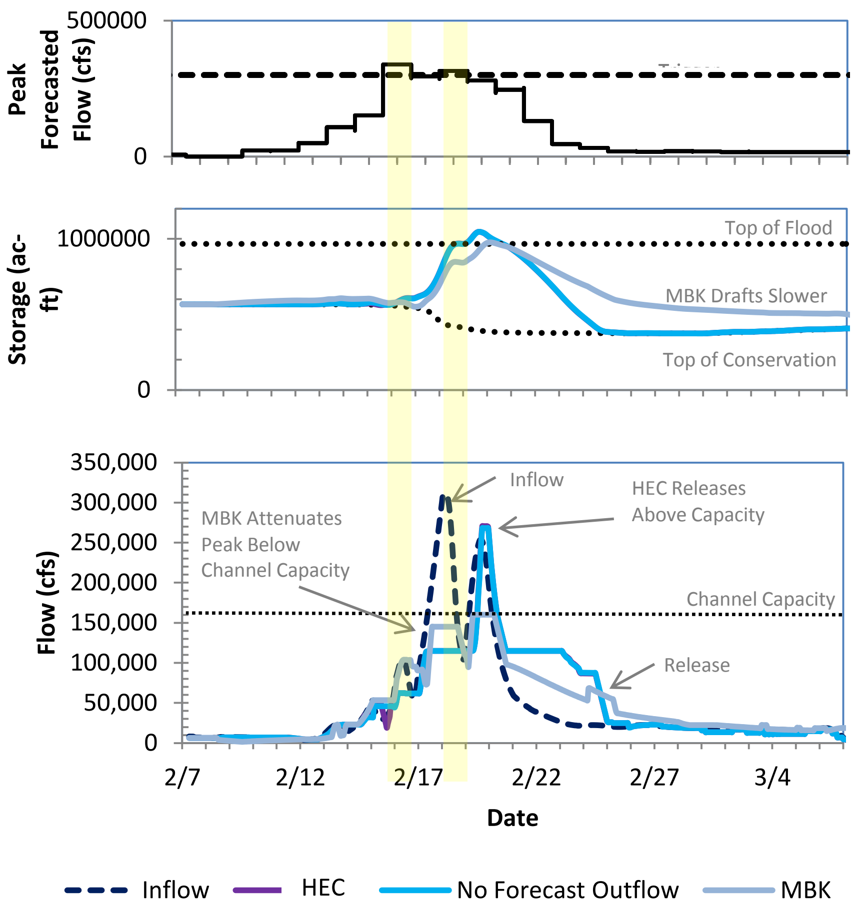

Figure 19 (i)

200-year 1986 Shape, 600 TAF Starting Storage

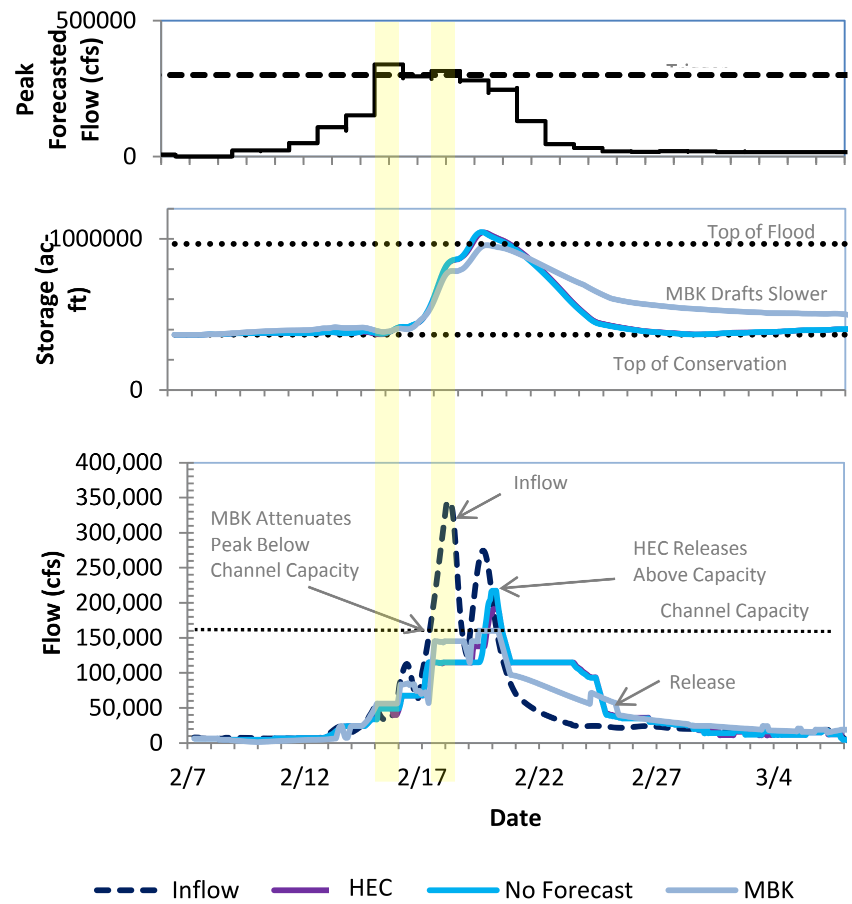

Figure 19(j)

Figure 19, Continued

200-year 1997 Shape, 400 TAF Starting Storage

200-year 1997 Shape, 600 TAF Starting Storage

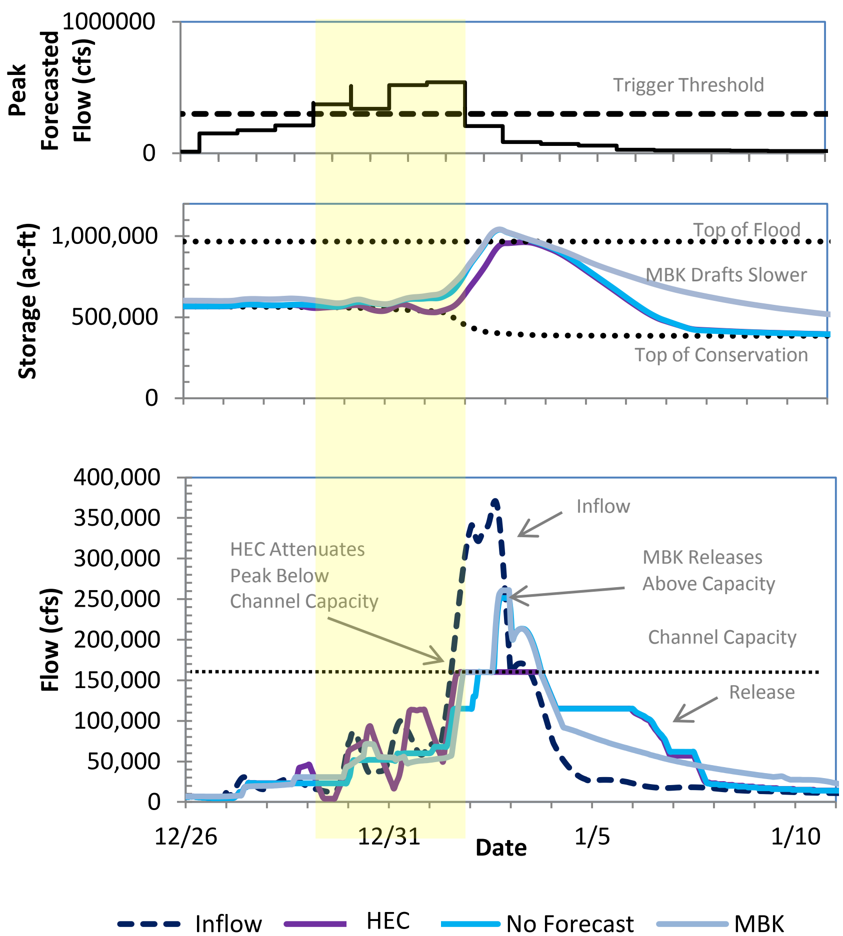

Figure 19(k)

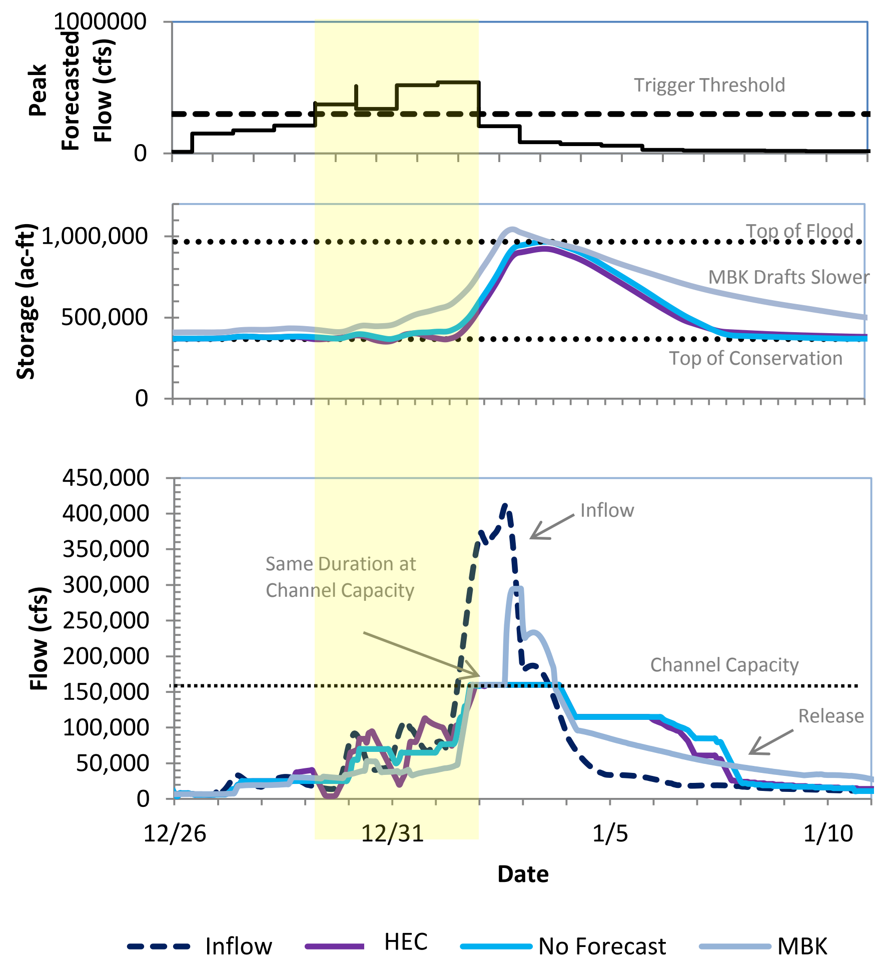

Figure 19(l)

Figure 19, Continued.

Table 11a. 1-in-200 Year Event. Comparison of HEC and MBK Rules

400	PMF	PMF	SPF	SPF	1955	1955	1964	1964	1986	1986	1997	1997
Rule	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK
Peak Storage (TAF)	970.3	1012	1022	940.4	999.4	979.7	924.7	963.4	1047	977.4	963.5	1041
Peak Outflow (cfs)	160	**174**	**191**	160	160	160	160	160	**271**	160	160	**261**
Duration >115 kcfs (hr)	61	50	59	54	61	57	66	64	137	69	62	58
Duration >160 kcfs (hr)	0	8	15	0	0	0	0	0	21	0	0	28
Failure Probability	9%	**100%**	**100%**	7%	7%	9%	10%	9%	**100%**	13%	10%%	**100%**

Table 11b. 1-in-200 Year Event. Comparison of HEC and MBK Rules. Maximum Space in the Flood Pool

600	PMF	PMF	SPF	SPF	1955	1955	1964	1964	1986	1986	1997	1997
Rule	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK
Peak Storage (TAF)	961.5	977.8	1003	943.8	952.3	924.0	891.9	954.3	1043	957.7	922.7	1042
Peak Outflow(cfs)	160	160	160	160	160	160	160	160	**191**	160	160	**295**
Duration >115 kcfs (hr)	59	56	53	55	58	59	72	62	143	77	61	57
Duration >160 kcfs (hr)	0	0	0	0	0	0	0	0	18	0	0	27
Failure Probability	9%	8%	7%	6%	7%	7%	10%	7%	**100%**	15%	8%	**100%**

In general, the MBK rule transitioned more smoothly and gradually from lower flows to higher flows, and back down to guide curve after the flood. The releases were constrained frequently by the guide curve, similar to the HEC-based rule. Releases are activated earlier for the MBK rule but are lower than the proposed rule in several cases. With the exception of the 1997 shape and the PMF shape, storage for the MBK rule is typically lower than the storage for the proposed rule before the peak passes, and higher than the storage for the proposed rule after the hydrograph peak has passed. The MBK rule's accelerated transition objective (ramp up releases while maximizing water storage in flood pool) is responsible for the increased storage after the peak passes and the smoothing routine objective (minimize storage in flood pool) is responsible for decreased storage before the peak passes. Since the modified HEC formulation has only one objective, which is to ramp up increases while maximizing water storage in the flood pool, peak storage is generally lower and peak releases are generally higher for the HEC-formulated rule than for the MBK-formulated rule.

As Table 11a and Table 11ab show, the 99% rule exceeded channel capacity for three of the 12 scenarios using on-time but imperfect artificial forecasts; the MBK rule exceeded channel capacity for four of the 12 scenarios using on-time but imperfect artificial forecasts. MBK reduced the peak more than the 99% rule for the 1986-shaped scenario with minimum storage space in the flood pool, and for the SPF shape starting with minimum storage space in the flood pool. 99% rule reduced the peak for both 1997 scenarios and for the 1986-shaped scenario with maximum storage space in the flood pool.

However, although the MBK formulation is promising, it does not incorporate uncertainty and the simulation did not recognize that the artificial forecasts used("on-time" forecasts, Appendix B) were imperfect. Incorporating uncertainty would reduce the responsiveness of the MBK rule—perhaps limiting the peak reduction. The MBK rule could exceed channel capacity more frequently or lead to higher outflows for the times when outflow is already exceeded. When uncertainty is incorporated into the MBK rule, further analysis should be completed.

7.7. Lead time

Lead times other than 72 hours may be chosen to increase certainty and decrease the aggressiveness of the rule, although forecast error has not been proven to increase with lead time. The rules were tested to determine the sensitivity to changes in the lead-time of the forecasts. Lead times of 24, 48, and 72 hours were tested and compared using the artificial on-time forecasts (Appendix B). Figure 20, below, shows the operations.

200-year PMF Shape, 400 TAF Starting Storage

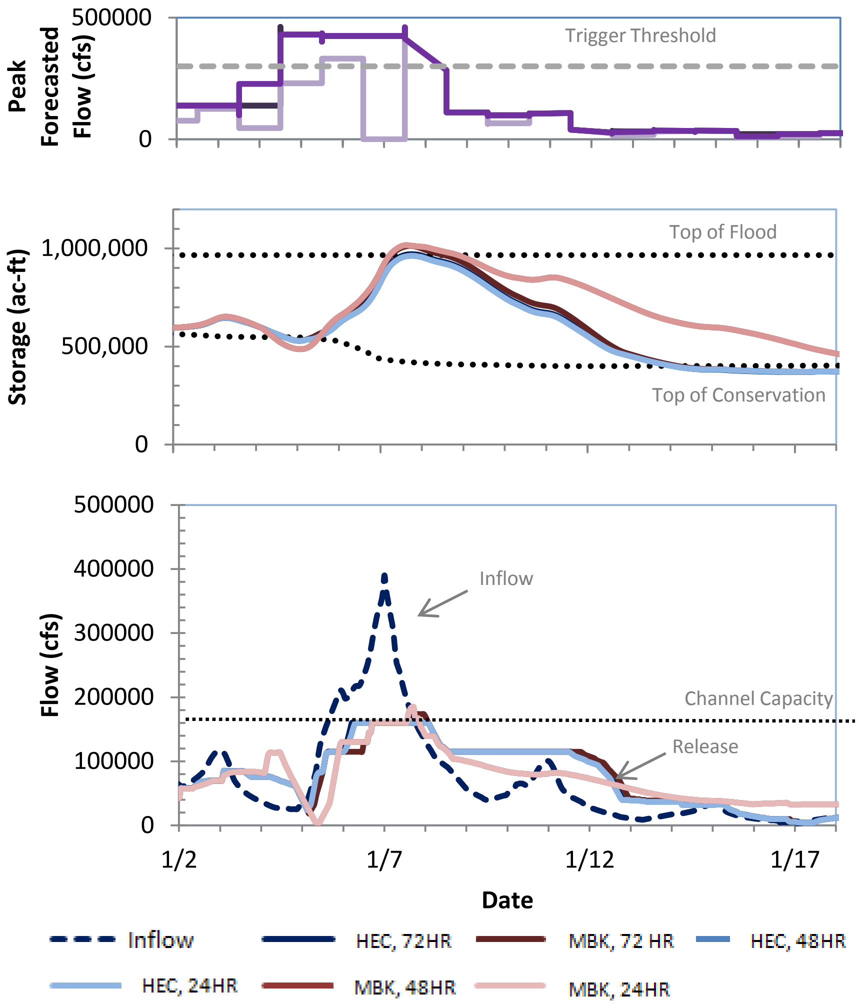

Figure 20.(a)

200-year PMF Shape, 600 TAF Starting Storage

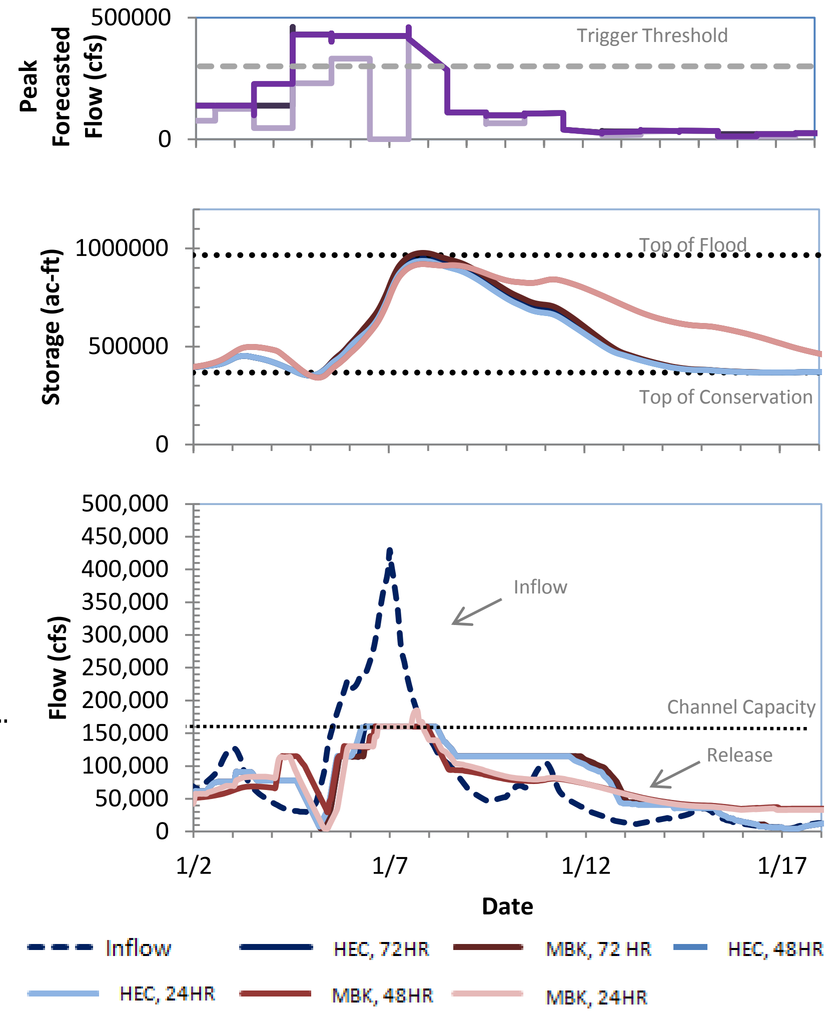

Figure 20. (b)

Figure 20. Lead Time

200-year SPF Shape, 400 TAF Starting Storage

200-year SPF Shape, 600 TAF Starting Storage

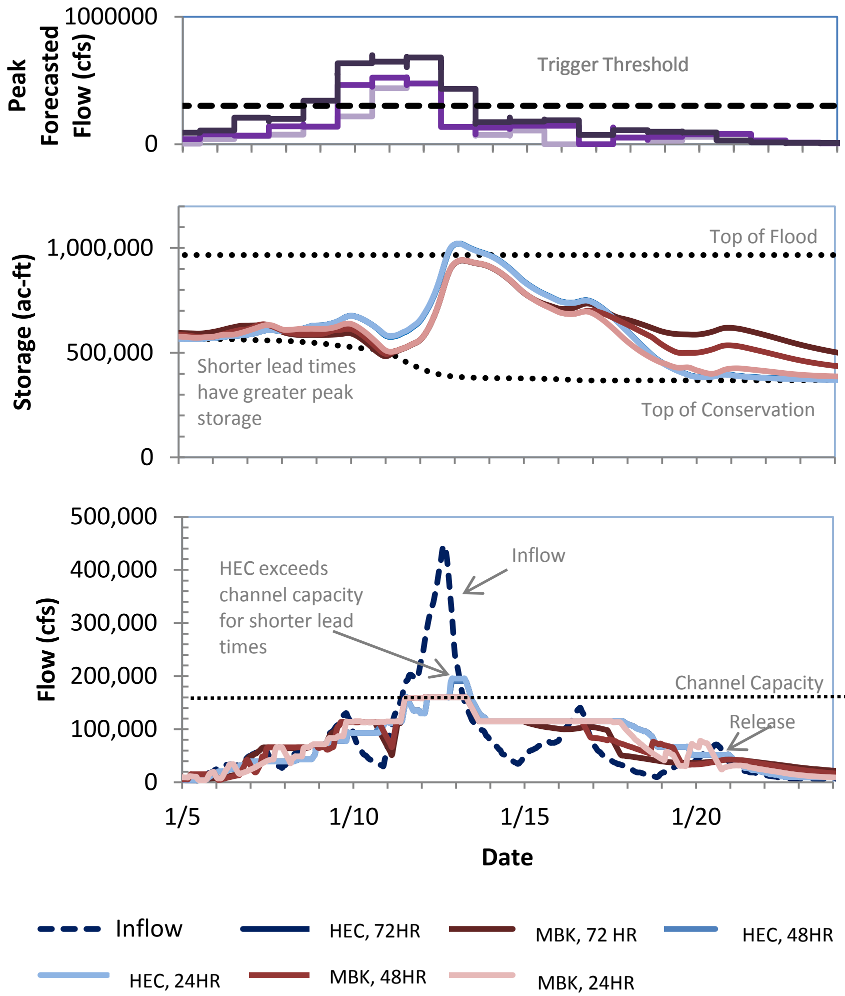

Figure 20.(c)

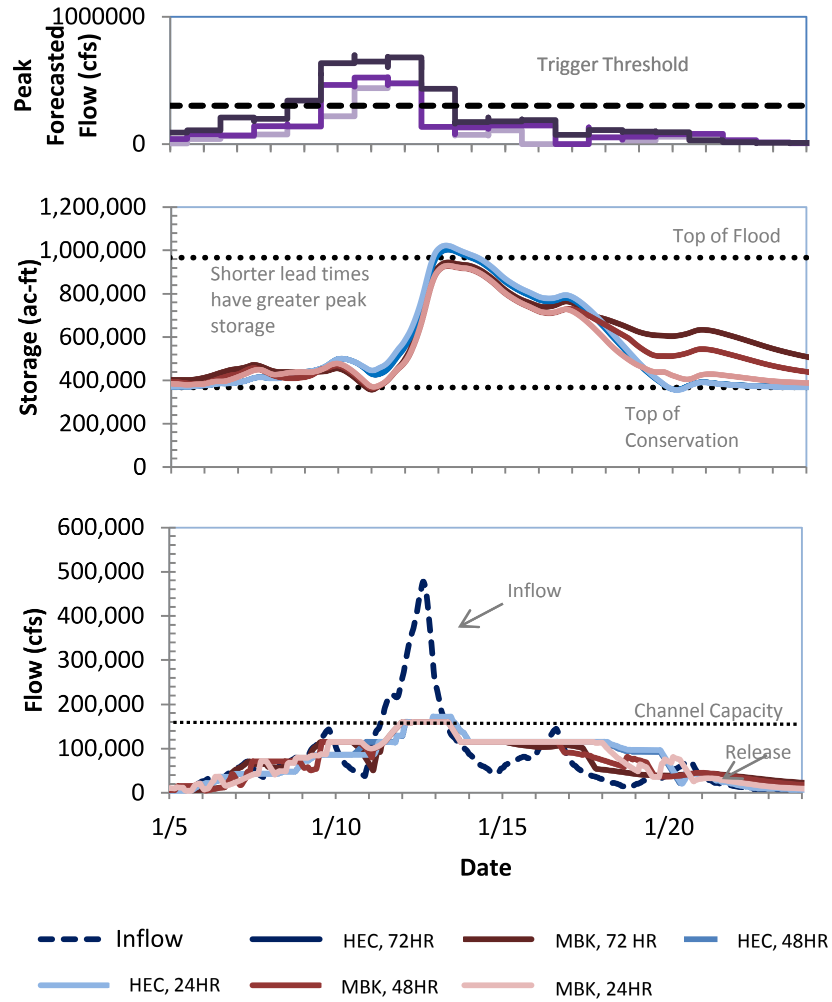

Figure 20. (d)

Figure 20. Continued

200-year 1955 Shape, 400 TAF Starting Storage

200-year 1955 Shape, 600 TAF Starting Storage

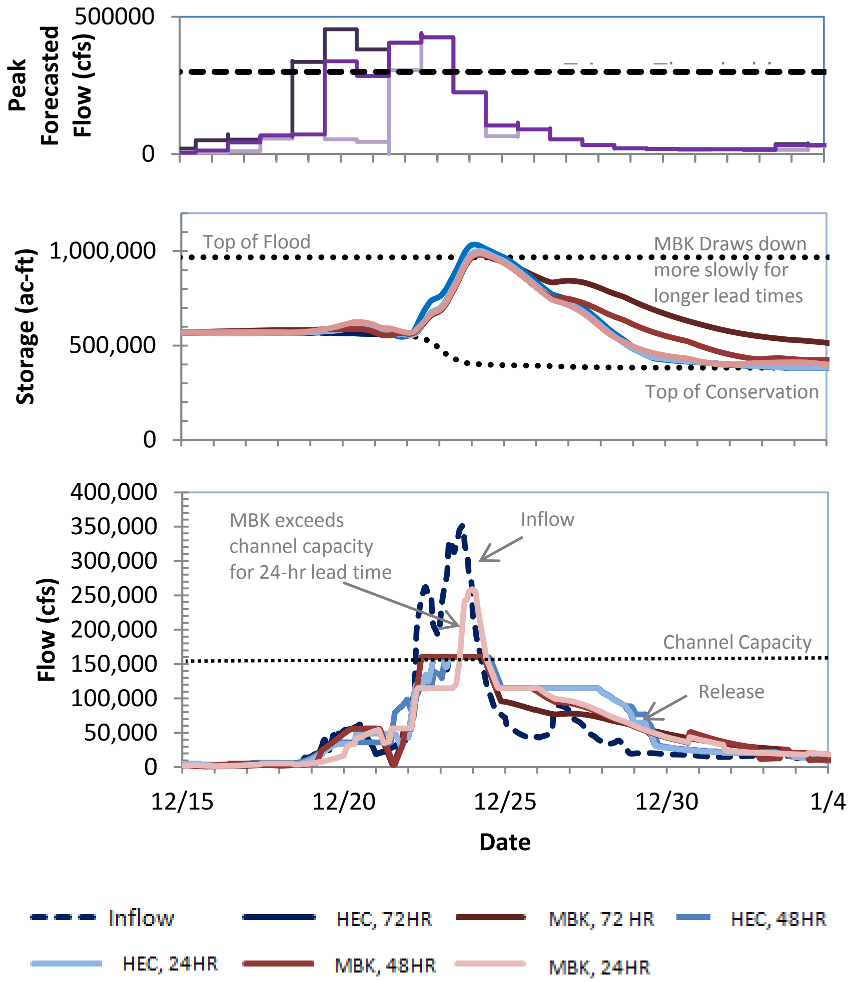

Figure 20.(e)

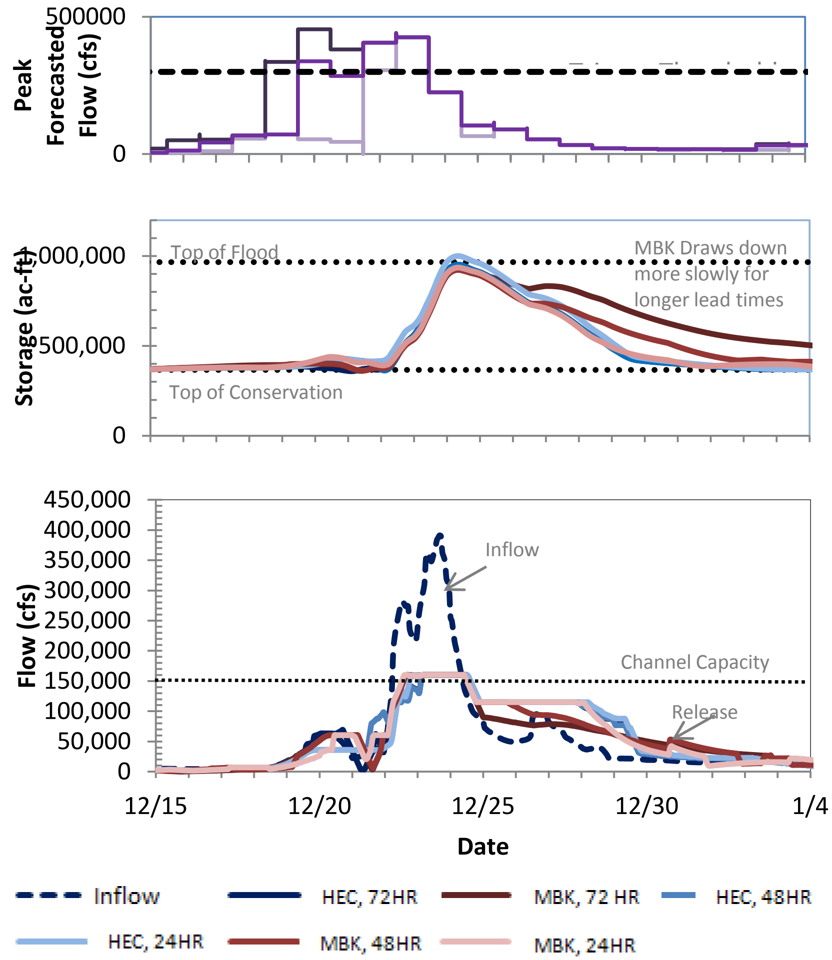

Figure 20. (f)

Figure 20. Continued

200-year 1964 Shape, 400 TAF Starting Storage

200-year 1964 Shape, 600 TAF Starting Storage

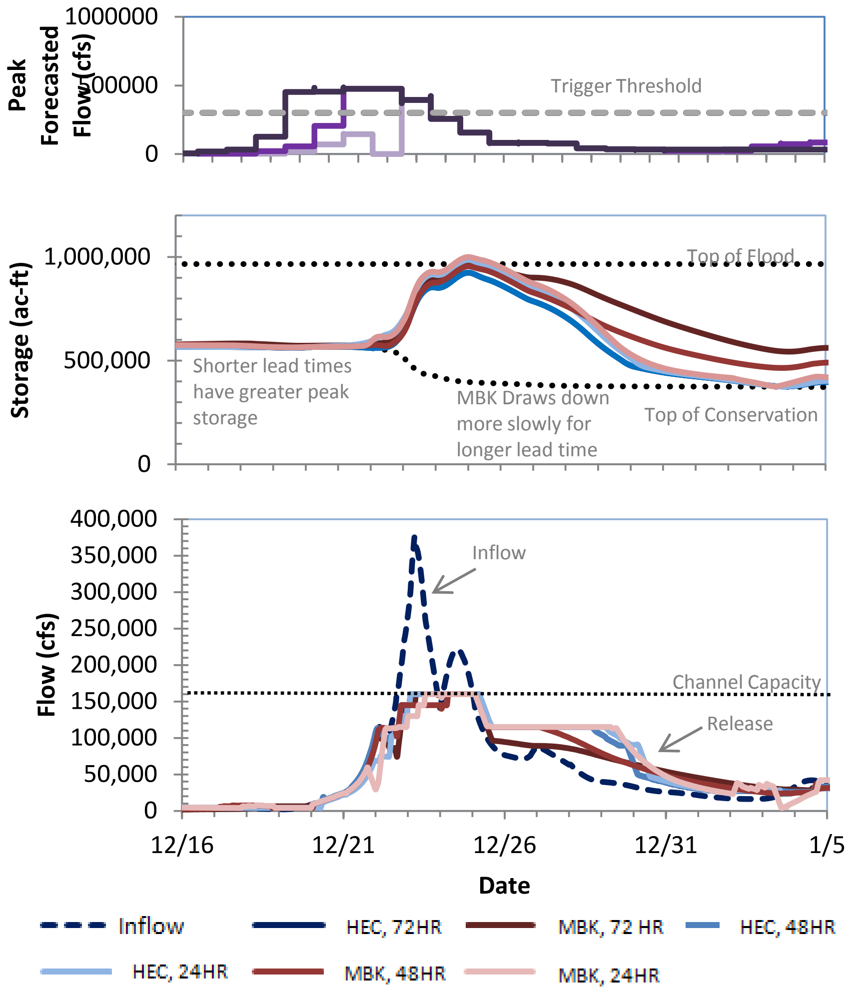

Figure 20.(g)

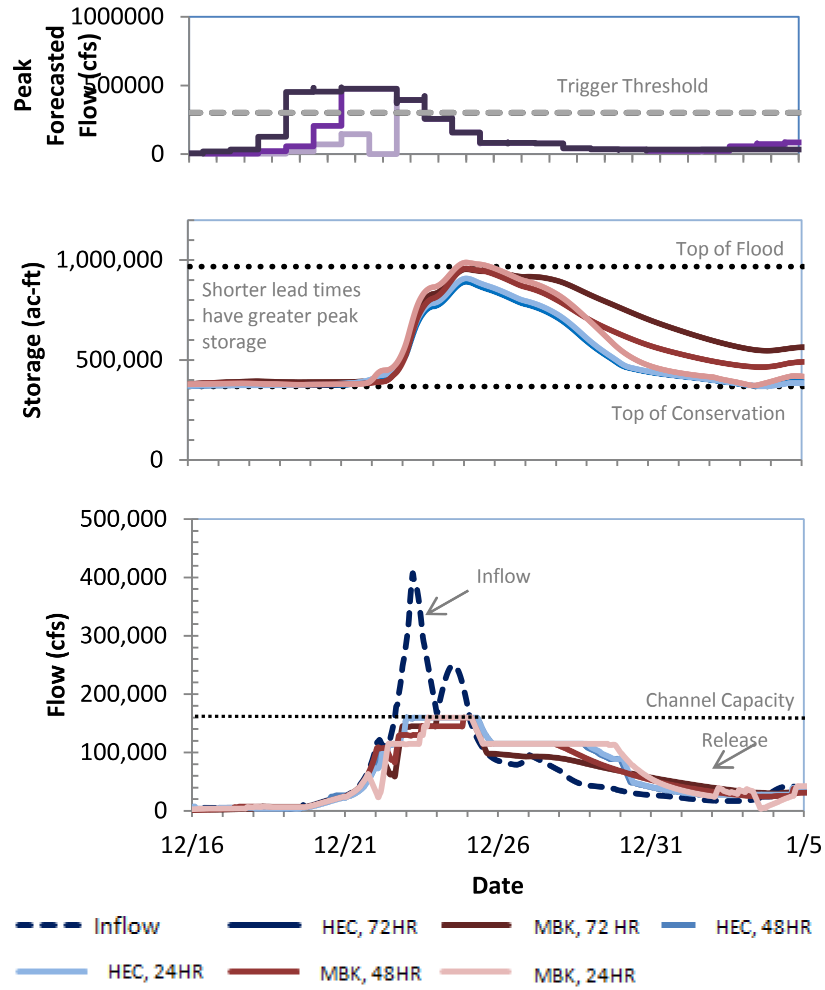

Figure 20. (h)

Figure 20. Continued

200-year 1986 Shape, 400 TAF Starting Storage

200-year 1986 Shape, 600 TAF Starting Storage

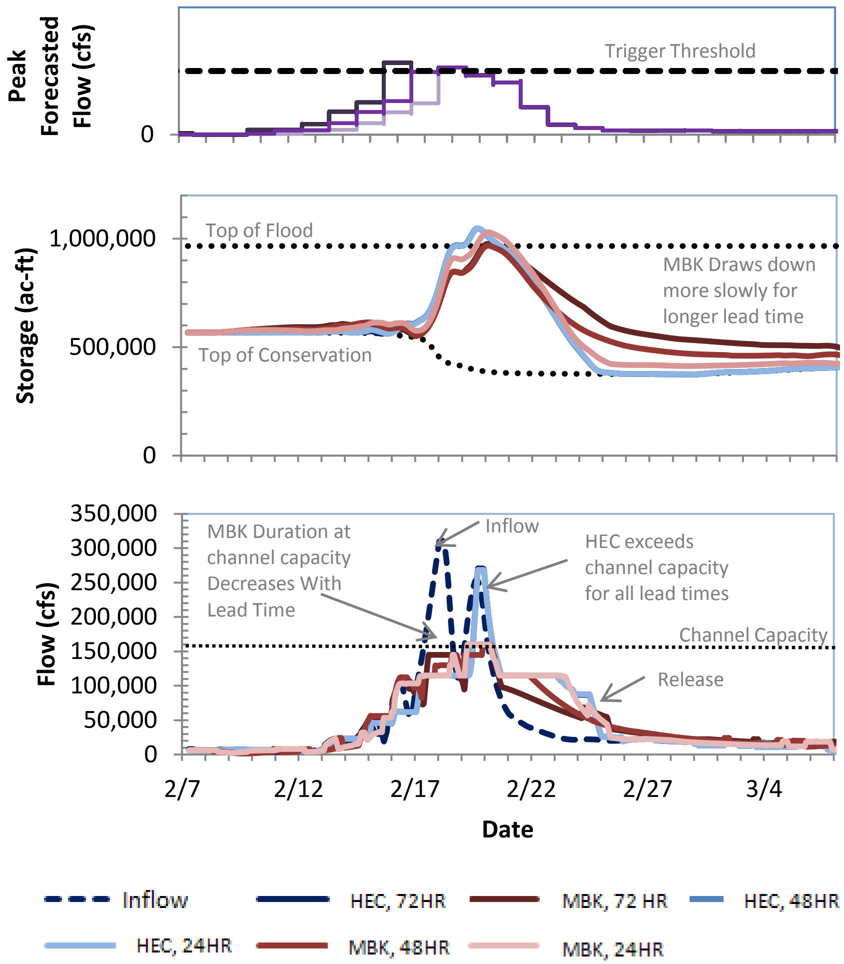

Figure 20.(i)

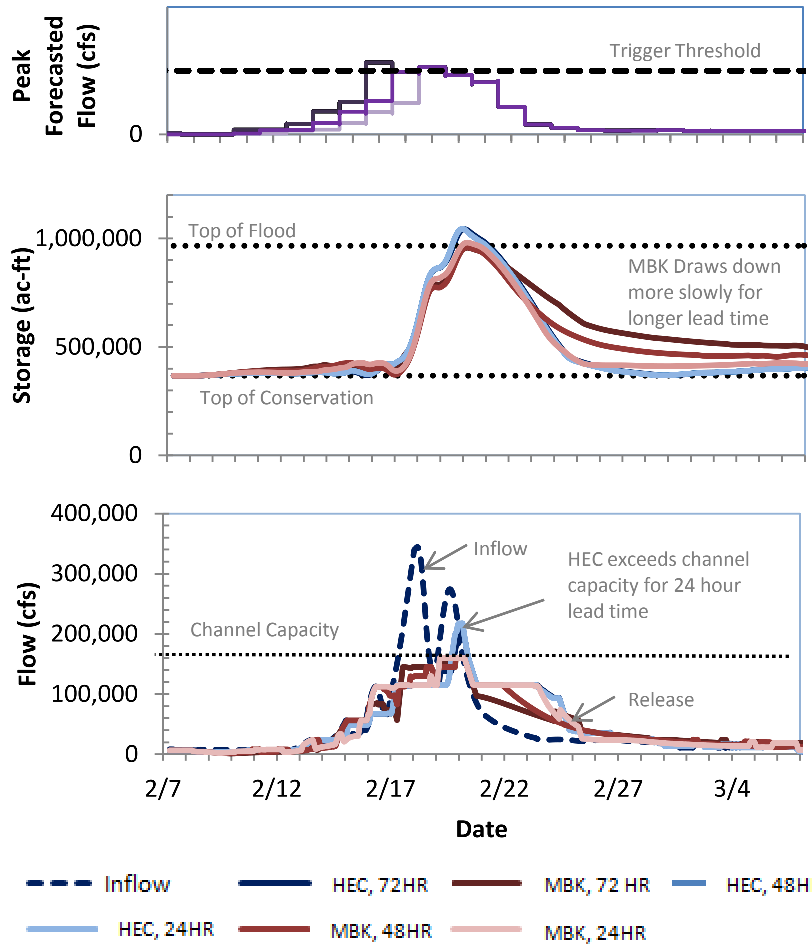

Figure 20. (j)

Figure 20. Continued

200-year 1997 Shape, 400 TAF Starting Storage

200-year 1997 Shape, 600 TAF Starting Storage

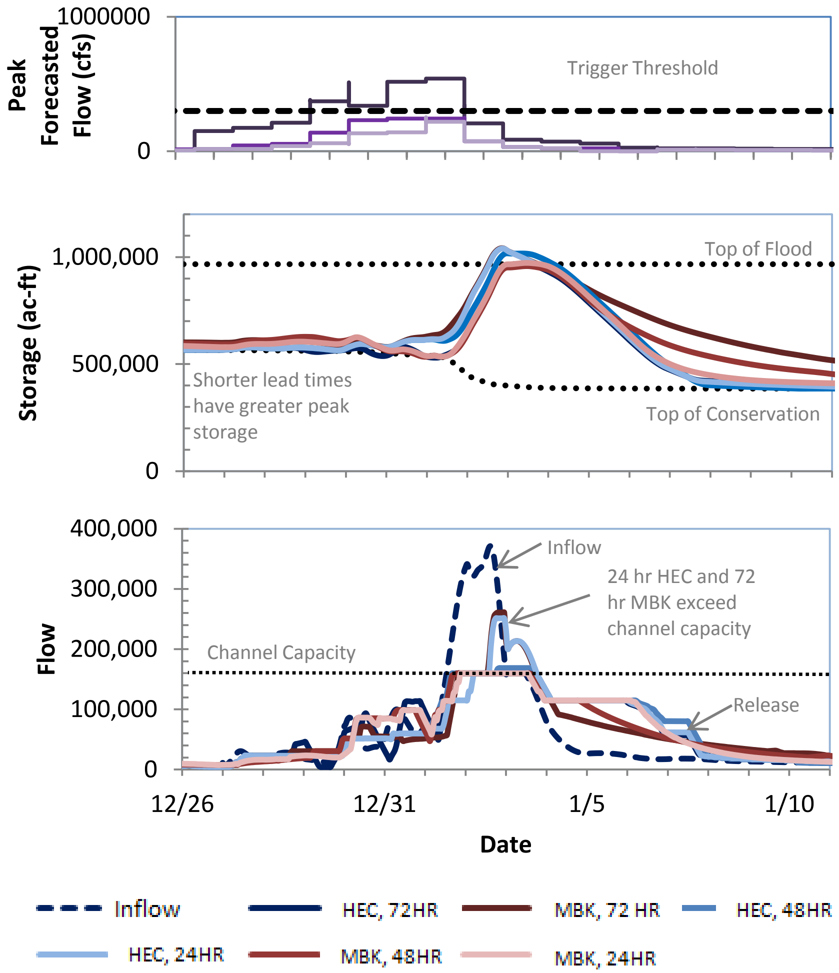

Figure 20.(k)

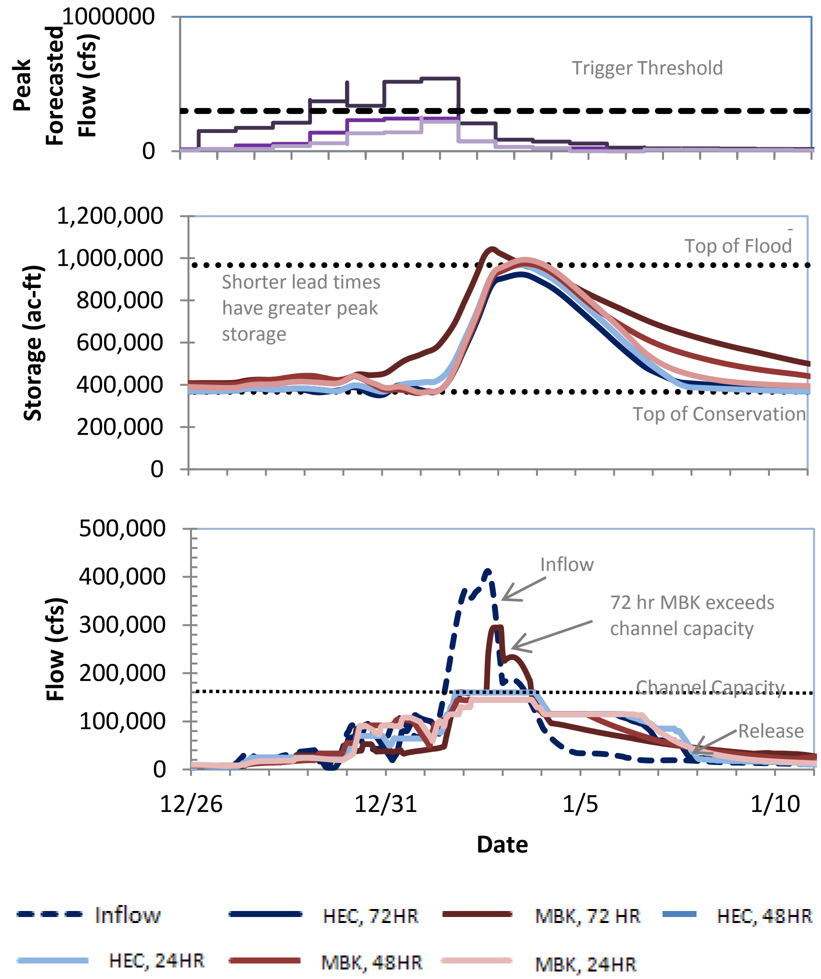

Figure 20. (l)

Figure 20. Continued

Table 12a. 1-in-200 year Operations—HEC and MBK Rules with Varying Lead Time

PMF	400	400	400	400	400	400	600	600	600	600	600	600

Rule	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK
Lead Time (hr)	72hr	72hr	48hr	48hr	24hr	24hr	72hr	72hr	48hr	48hr	24hr	24hr
Peak Storage (TAF)	970.4	1013	962.8	1016	962.8	1016	961.5	977.8	935.9	919.6	935.9	919.6
Peak Outflow (cfs)	160	**173**	160	**184**	160	**184**	160	160	160	160	160	**184**
Duration >115 kcfs (hr)	61	50	61	63	61	63	59	56	64	60	64	63
Duration >160 kcfs (hr)	0	8	0	7	0	7	0	0	0	0	0	7
Failure Probability	9%	**100%**	8%	**100%**	8%	**100%**	9%	8%	9%	7%	9%	**100%**

Table 12b. 1-in-200 year Operations—HEC and MBK Rules with Varying Lead Time

SPF	400	400	400	400	400	400	600	600	600	600	600	600
Rule	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK
Lead Time (hr)	72hr	72hr	48hr	48hr	24hr	24hr	72hr	72hr	48hr	48hr	24hr	24hr
Peak Storage (TAF)	1022	940.4	1022	942.9	1022	942.1	1003	943.9	1003	928.4	1023	929.5
Peak Outflow (kcfs)	**191**	160	**191**	160	**196**	160	160	160	160	160	**172**	160
Duration >115 kcfs (hr)	59	54	59	54	59	54	53	55	53	54	53	55
Duration >160 kcfs (hr)	15	0	15	0	15	0	0	0	0	0	16	0
Failure Probability	**100%**	7%	**100%**	7%	**100%**	7%	7%	6%	7%	6%	**100%**	6%

Table 12c. 1-in-200 year Operations—HEC and MBK Rules with Varying Lead Time

1956	400	400	400	400	400	400	600	600	600	600	600	600
Rule	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK
Lead Time (hr)	72hr	72hr	48hr	48hr	24hr	24hr	72hr	72hr	48hr	48hr	24hr	24hr
Peak Storage (ac-ft)	999.4	979.7	1035	982.0	1000	987.7	952.3	924.0	951.4	922.8	1000	935.2
Peak Outflow (cfs)	160	160	160	160	160	**258**	160	160	160	160	160	160
Duration >115 kcfs (hr)	61	58	57	58	59	33	58	59	57	59	60	60
Duration >160 kcfs (hr)	0	0	0	0	0	19	0	0	0	0	0	0
Failure Probability	7%	9%	7%	9%	7%	**100%**	7%	7%	7%	7%	8%	7%

Table 12d. 1-in-200 year Operations—HEC and MBK Rules with Varying Lead Time

1965	400	400	400	400	400	400	600	600	600	600	600	600

Rule	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK
Lead Time (hr)	72hr	72hr	48hr	48hr	24hr	24hr	72hr	72hr	48hr	48hr	24hr	24hr
Peak Storage (ac-ft)	924.7	963.4	924.7	955.7	986.0	999.8	891.9	954.3	891.7	957.0	987.9	1015
Peak Outflow (cfs)	160	160	160	160	160	160	160	160	160	160	160	160
Duration >115 kcfs (hr)	66	62	66	66	66	63	72	64	72	66	72	57
Duration >160 kcfs (hr)	0	0	0	0	0	0	0	0	0	0	0	0
Failure Probability	10%	9%	10%	6%	10%	8%	10%	7%	10%	3%	10%	7%

Table 12e. 1-in-200 year Operations—HEC and MBK Rules with Varying Lead Time

1986	400	400	400	400	400	400	600	600	600	600	600	600
Rule	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK
Lead Time (hr)	72hr	72hr	48hr	48hr	24hr	24hr	72hr	72hr	48hr	48hr	24hr	24hr
Peak Storage (ac-ft)	1047	977.4	1047	967.8	1047	1030	1043	957.7	1044	958.9	1045	980.8
Peak Outflow (cfs)	**271**	160	**268**	160	**268**	160	**191**	160	**217**	160	**217**	160
Duration >115 kcfs (hr)	137	69	137	109	137	142	143	77	142	102	142	138
Duration >160 kcfs (hr)	21	0	20	0	20	0	16	0	18	0	18	0
Failure Probability	**100%**	13%	**100%**	11%	**100%**	8%	**100%**	15%	**100%**	11%	**100%**	8%

Table 12f. 1-in-200 year Operations—HEC and MBK Rules with Varying Lead Time

1997	400	400	400	400	400	400	600	600	600	600	600	600
Rule	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK	HEC	MBK
Lead Time (hr)	72hr	72hr	48hr	48hr	24hr	24hr	72hr	72hr	48hr	48hr	24hr	24hr
Peak Storage (ac-ft)	963.5	1041	1017	958.5	1040	972.9	922.7	1042	966.7	974.2	966.7	993.1
Peak Outflow (cfs)	160	**261**	**169**	160	**251**	160	160	**295**	160	145	160	145
Duration >115 kcfs (hr)	62	58	62	57	49	54	61	57	61	57	61	52
Duration >160 kcfs (hr)	0	28	24	0	29	0	0	27	0	0	0	0
Failure Probability	10%	**100%**	**100%**	9%	**100%**	8%	8%	**100%**	9%	2%	9%	2%

In general, a shorter lead time leads to a later reaction. The results of this later reaction can vary by event shape; for the 1956 and 1965 event shapes, the shorter lead time did not reduce or increase the peak. For the PMF, SPF, 1986, and 1997 shapes with on-time artificial forecasts, the shorter lead times led to higher peaks since advance release did not initiate early enough. The MBK rule provided greater peak attenuation for the PMF and 1986 shapes; the modified HEC rule provided higher attenuation for the SPF and 1997 shape. However, although the MBK rule was simulated using the same imperfect forecast as the modified HEC rule (the "on-time" forecast) the MBK rule does not include uncertainty in the release computation, and when uncertainty is included the peak attenuation may be less.

For both rules, shorter lead times generally increase peak storage in the reservoir. Figure 21, below, demonstrates these trends. MBK rule typically has a higher peak storage than the proposed rule.

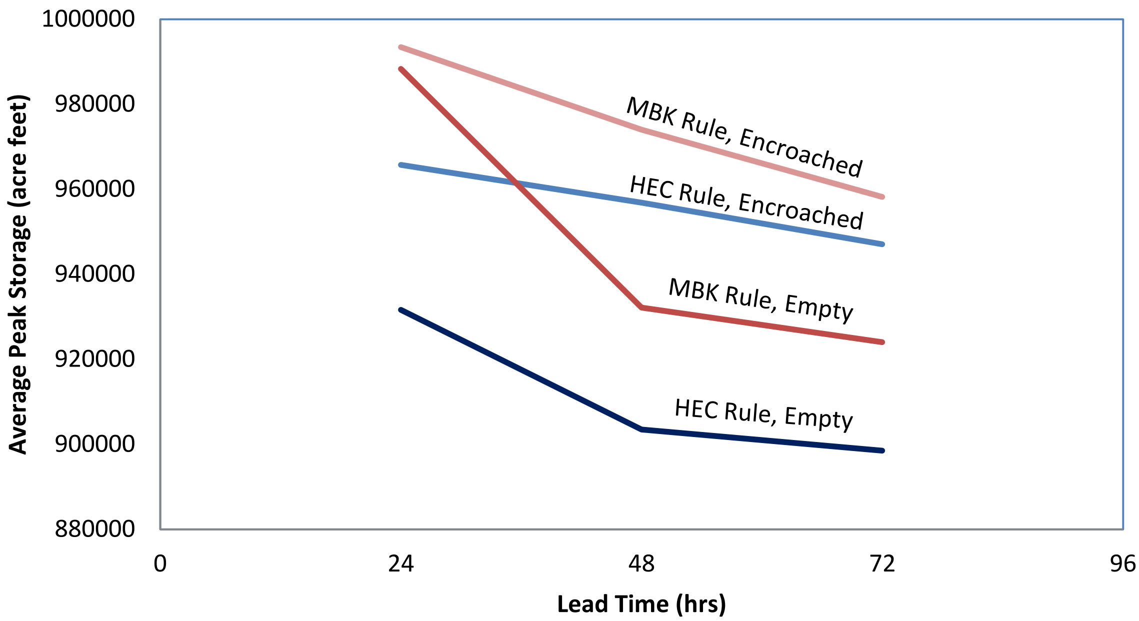

Figure 21. Average Peak Storage vs. Lead Time.

As the slopes of Figure 21. Average Peak Storage vs. Lead Time. demonstrate, lead time has a more pronounced effect on storage when the simulations initialize with maximum space in the flood pool. Since the space available in the reservoir is greater, and higher flows are not seen due to the shorter lead time, computed release volumes are lower. This increases storage. With short lead times, releases are not made until more encroachment occurs. When the reservoir is initialized at its highest guide curve and minimum space in the flood pool, however, the decreased space available in the reservoir is more prominent in the computation, counteracting the fact that high flows are not seen in advance. This slightly reduces the effect of lead time, although shorter lead time still clearly increases storage.

7.8. Summary

The results from all of the rules simulated were summarized by incorporating the relative weights of each shape (determined in Section 6.2 of this paper). Rules were compared based on the weighted average of hours exceeding 115,000 cfs and the weighted average of the estimated failure probability. Probability of exceeding 160,000 cfs for each rule was determined by determining the proportion out of the 12 scenarios where the peak exceeded 160,000 cfs. Table 13 below summarizes the results without downstream levee improvements, ranked first by refill probability and then by estimated failure probability. * The original HEC Rule allows advance release from the conservation pool. The modified HEC Rule does not.

Table 14 provides the same summary for results *with* downstream levee improvements.

Table 13. Ranking of Rules based on Downstream Performance (Without Improvements)

Rank	Base Rule	Advance Release Conservation Water?	Trigger (forecasted kcfs)	Forecast	Lead Time (Hrs)	Refill Probability	Prob. Exceeding 160 kcfs	EV Hours Exceeding 115 kcfs (hrs)	EV Failure
1	HEC	No	300	High	72	99%	0.08	62	17.2%
2	HEC	No	300	Late	72	99%	0.25	58	27.6%
3	**HEC**	**No**	**300**	**On Time**	**72**	**99%**	**0.25**	**56**	**35.7%**
4	HEC	No	200	On Time	72	99%	0.25	56	35.7%
5	HEC	No	300	Perfect	72	99%	0.33	58	37.7%
6	HEC	No	300	Early	72	99%	0.33	54	41.8%
7	HEC	Yes*	300	On Time	72	99%	0.33	55	48.4%
8	HEC	No	300	Perfect	48	99%	0.33	55	48.6%
9	HEC	No	500	On Time	72	99%	0.33	53	53.1%
10	HEC	No	300	Perfect	24	99%	0.42	53	53.3%
11	HEC	No	300	Low	72	99%	0.50	52	59.2%
12	HEC	No	300	On Time	72	98%	0.08	58	21.5%
13	HEC	No	300	Perfect	72	98%	0.25	59	30.4%
14	HEC	Yes*	300	On Time	72	98%	0.25	51	38.3%
15	HEC	No	300	On Time	72	95%	0.08	60	21.9%
16	HEC	No	300	Perfect	72	95%	0.08	59	22.5%
17	HEC	Yes*	300	On Time	72	95%	0.17	54	34.2%
18	MBK	No	--	On Time	48	--	0.00	61	15.7%
19	MBK	No	--	On Time	24	--	0.17	52	25.0%
20	HEC	No	300	Perfect	72	--	0.17	59	28.5%
21	MBK	No	--	On Time	72	--	0.17	61	44.2%
	Without Forecasts	No	--	--	--	--	0.58	49	70.0%

* The original HEC Rule allows advance release from the conservation pool. The modified HEC Rule does not.

Table 14. Ranking of Rules based on Downstream Performance (With Project)

Rank	Base Rule	Advance Release Conservation Water?	Trigger (forecasted kcfs)	Forecast	Lead Time (Hrs)	Refill Probability	Prob. Exceeding 160 kcfs	EV Hours Exceeding 115 kcfs (hrs)	EV Failure
1	HEC	No	300	High	72	99%	0.08	62	13.8%
2	HEC	No	300	Late	72	99%	0.25	58	24.4%
3	**HEC**	**No**	**300**	**On Time**	**72**	**99%**	**0.25**	**56**	**35.1%**
4	HEC	No	200	On Time	72	99%	0.25	56	35.1%
5	HEC	No	300	Perfect	72	99%	0.33	58	35.4%
6	HEC	No	300	Early	72	99%	0.33	54	41.2%
7	HEC	Yes*	300	On Time	72	99%	0.33	55	48.0%
8	HEC	No	300	Perfect	48	99%	0.33	55	48.1%
9	HEC	No	500	On Time	72	99%	0.33	53	52.6%
10	HEC	No	300	Perfect	24	99%	0.42	53	52.8%
11	HEC	No	300	Low	72	99%	0.50	52	58.8%
12	HEC	No	300	On Time	72	98%	0.08	58	19.6%
13	HEC	No	300	Perfect	72	98%	0.25	59	28.6%
14	HEC	Yes*	300	On Time	72	98%	0.25	51	36.6%
15	HEC	No	300	On Time	72	95%	0.08	60	19.9%
16	HEC	No	300	Perfect	72	95%	0.08	59	20.1%
17	HEC	Yes*	300	On Time	72	95%	0.17	54	32.3%
18	MBK	No	--	On Time	48	--	0.00	61	11.9%
19	MBK	No	--	On Time	24	--	0.17	52	22.3%
20	HEC	No	300	Perfect	72	--	0.17	59	26.2%
21	MBK	No	--	On Time	72	--	0.17	61	40.3%
	Without Forecasts	No	--	--	--	--	0.58	49	69.7%

* The original HEC Rule allows advance release from the conservation pool. The modified HEC Rule does not.

- Perfect forecasts (Rank 5, 13, and 16) did not always have lower failure probabilities than imperfect forecasts (Rank 3, 12, and 15) because the rules assumed they were imperfect.
- Early and low forecasts (Rank 6 and 11) challenged the rule's performance more than high and late forecasts (Rank 1 and 2) although the probabilities of failure were reduced for all cases from 11% to 56% compared to the operation without forecasts.
- Longer lead times limited the performance of the MBK rule but not the modified HEC rule. The MBK rule with 72 hour lead time ranked the lowest (rank 21 in Table 13) and produced a higher expected value of failure. HEC formulation, modified to operate only in the flood pool with 99% refill probability and 72-hour forecast peak greater than 300 kcfs, was ranked 3.
- The ranking for the rules was similar regardless of downstream levee improvements or no downstream levee improvements; expected value of levee failure for the proposed rule ranges between 35.1% (with improvements) and 35.7% (without improvements) for a 200-year flood.
- The use of forecasts reduces the magnitude and duration of flows on downstream levees for the 200-year flood. Based on preliminary hydrograph scaling and geotechnical curves, the overall risk of downstream levee failure can be reduced 30 percent or more if the operations use 99% refill probability.
- The risk of downstream failure can be reduced even more--up to 50 percent--if the operations use 98% refill probability. Reducing the refill probability of operations to 95% appears to provide little additional performance, and risk of failure is still only reduced up to 50%.
- Due to the challenges from imperfect forecasts, rules which incorporate uncertainty and refill probabilities are very important and were thus ranked highest. Although a 98% refill probability greatly reduces flooding probability with only slightly more water supply risks, USACE guidance is to avoid unnecessary early releases to the maximum extent possible. The proposed rule to minimize unnecessary releases, HEC with a 99% refill probability (1% quantile) is shown in bold (rank 3 in Table 13 and * The original HEC Rule allows advance release from the conservation pool. The modified HEC Rule does not.
- Table 14).
- Due to recreational use of the channel and temporary infrastructure within the channel, increases in forecast releases should correspond with appropriate warnings to downstream parties and should obey established rate-of-change limits.
- The performance of the rules relative to each other appears to be the same whether or not downstream levees are improved, although the risk for all rules is lower if downstream levee improvements are made.
- Responsiveness of the rules for the 200-year flood is limited by too small an incoming forecasted volume or too large a current available space; larger floods would have correspondingly larger forecasts and higher storage in the flood pool, resulting in higher releases and a more active forecast rule. In future studies, the rules refined from the 200-year simulations should be used to route larger hydrographs and demonstrate the benefits or performance trade-offs for more extreme floods.

8. Discussion

The results of the model runs must be evaluated with the understanding that the artificial forecasts are not real forecasts; although they are possible, the artificial forecasts simulated in this study are not necessarily the most probable. Nevertheless, using artificial forecasts rather than real or perfect forecasts allowed for testing of a wide variety of cases, and allowed for creation of more robust rules. Further, it is important to distinguish between retrospectively simulating the best operation for the event when the outcome is known, and simulating the operator's decision based on the information known at each point in time, when the outcome is not known.

The consequences of forecast-based advance release vary. Negative consequences could include water supply reduction, unnecessary channel damage, and water quality impacts—the cold water pool may be reduced by the advance release, and even if refill occurs the refilled water might not be of equivalent quality. Hydropower energy spill, impacts to sensitive species, and early loss of downstream infrastructure could also occur from unnecessarily high releases. Positive consequences could include reduced flood damage and life-loss downstream—the peak flow could be reduced by releasing earlier. In addition, the proposed rules could provide benefits for floods rarer than 200-year; the 500-year flood and more extreme scalings ought to be simulated in the future to evaluate the benefits of forecast operations for such rare events.

Implementing releases earlier may also affect downstream warning times between low flow and channel-capacity flow. Before construction of the auxiliary spillway, operators could not release water until the pool reached the elevation of the existing spillway. This inability to release water provided additional warning time—operators could see that large releases needed to be made before the spillway was reached, and could alert those downstream to take appropriate action. Future implementation of this rule may need to include additional release limits; the current rule threshold is set to 160,000. Below 160,000 cfs the release limit is 115,000 cfs. Similar to the Shasta release diagram, different release schedules could be provided based on the expected size of the flood, and the current inflow. Such a structure could allow for pauses at important thresholds.

The current rule curve is set based on a maximum 600 TAF flood pool; releases during flood operations must not draw the reservoir below this guide curve. However, other studies for the reoperation of Folsom may adjust the guide curves upward and decrease the flood storage space based on basin wetness parameters and storage credits from upstream reservoirs. Forecast based operation would be useful in transitioning between a high guide curve and flood operations. A flood pool larger than 600 TAF may also be considered, if it is needed to meet the JFP's target 1/200 year outflow of 160,000 cfs or less.

In terms of erosion and levee stability, it is uncertain whether a prolonged flow at 115,000 provides improvement over a brief flow at 160,000. Future operation studies should investigate the critical flows and durations for levee failure more rigorously, and should quantify the uncertainty in the fragility curves; operation plans could then be better optimized for downstream interests.

9. Conclusion and Recommendation

Due to the variability in hydrograph shapes, and the differing priorities for operating rules, outflows do not vary linearly or predictably with any of the variables examined in this study (start trigger, timing errors, magnitude errors, and refill probabilities). However, some conclusions and recommendations can be made.

Without forecast-based operations, 7 of the 12 cases proved problematic and only 5 maintained 200-year flows below 160,000 cfs. The addition of the proposed forecast-based rule to the operation set reduced or maintained 9 of the 12 outflows below 160,000. The expected probability of failure—based on estimated hydrograph weights, generic fragility curves for downstream levees, and the assumption of a 3 day critical duration for levee failure—was 70% for operations without forecast-based rule additions, and 35% for operations with proposed rule additions. With the forecast-based rule addition, 2 of the 3 cases remaining with flows above 160,000 had flows reduced by 15-25%. The 200-year 1986-shaped case starting with maximum space in the flood control pool remained challenging even with perfect forecasts. In all cases, the estimated combined risk of levee failure by erosion and overtopping was reduced.

No matter how low or high, a trigger based on flow will always lead to some false alarms. The rate of false alarms is currently unknown, but results were not determined to be sensitive to a volume-based start trigger. For this reason, a 300,000 cfs trigger is acceptable. However, forecast triggers which vary based on volume may be more reliable and meaningful, and should be tested in future studies.

If appropriate release limits are not specified, advance release rules could enable more water to be released than is actually incoming. For small floods with high forecasts, a high release before a flood could result in lost water supply or unnecessary downstream channel damage. The rule is thus formulated to limit the aggressiveness of the advance release based on the uncertainty in the forecast. USACE policy is to avoid any unnecessary advance release to the maximum extent possible. Therefore, releases should never exceed the volume the incoming hydrograph will be able to recover with 99% probability. In addition, advance release should be discontinued if the storage target has been reached and actual inflow recedes below 115,000 cfs, regardless of the forecast.

The use of the modified HEC rule in the conservation pool does not greatly affect the peak outflow, although it increases drawdown very effectively. Further study of the use of the conservation pool is suggested. If the reservoir starts with a higher guide curve due to the incorporation of wetness indices or other dynamic rule curves, the ability to draw water from the conservation pool to maintain a maximum 600 TAF of storage space could prove beneficial in the transition from the high rule curve to the lower rule curve.

The modified HEC rule with a 300 kcfs starting trigger, 99% refill probability, limited to the flood pool is recommended over the MBK rule since it incorporates uncertainty and improves attenuation for a greater number of event shapes and starting conditions. The MBK rule provides smooth transitions and peak attenuation for several events and could be refined to incorporate uncertainty; some elements of the MBK rule such as the smoothing routine and the FWS modification could also be incorporated into the proposed 99% rule. Rather than maintaining a low and steady advance release as intended by the original HEC formulation (which included conservation pool drafting), unintended spikes in releases still occur when releases are limited to the flood pool. For future implementation of the 99% rule or other modified versions of the HEC rule, an additional release limit will need to be developed and added to the operations —perhaps based on the current encroachment in the flood pool. Such adjustments would even out the unintended spikes and would be an important topic for further research.

Decreasing the forecast lead-time reduces the responsiveness of the resulting operations, leading to later reactions. The effects of the later reactions on peak outflows vary; however, decreased lead times usually increase water storage in the reservoir. Further, analysis of recent flood forecasts indicates that forecast error may not increase with lead times between 24 and 72 hours, although further study of the hindcasts will provide more conclusive results on the subject.

The model contains new rules with preliminary, placeholder statistics. Sensitivity analyses determined that the rule would be able to operate the reservoir effectively and reduce outflows to 160,000 or below for various types of imperfect forecasts. When available, the hindcasts should be analyzed to determine the range of forecast errors, and then the refill probability should be set. A target refill probability must be selected and the forecast errors must be thoroughly quantified to ensure that water supply is impacted as little as possible, and that high flows downstream are avoided where feasible. The fragility curve should also be refined to better determine the failure probability.

Although preliminary statistics have been used, and although the rest of the rules including the ESRD are subject to change during the reoperation study, the framework for analyzing forecasts and importing them into the model will be a practical tool for later planning studies. Operationally, the rule can be used in a simple spreadsheet model or in the current real-time ResSim model.

The forecast-based rules studied have so far only been implemented in simulation models for long-term planning purposes. Reservoir operators must communicate their planned releases to downstream interests to avoid unnecessary infrastructure damage. An operational forecast lists the series of planned future releases based on the current and future inflow and basin conditions. Thus far the thesis has been concerned with flow forecasts rather than operational forecasts. To simulate real time operation, the rule itself or a series of hypothetical releases prescribed by the rule could be input into the existing real time simulation model, and the rule could use the forecasts themselves as inflows rather than a summarized time-series of forecasted volumes and flows. In a real time model this rule will read the incoming forecast, alert the operator that an event is imminent, and calculate a minimum release to avoid surcharge. Existing rules such as the ESRD, rate-of-increase rule, and physical capacity of the spillway will ramp up outflows to the proposed minimum release, and will constrain outflows to a maximum release. The reservoir operator could communicate the forecast-based release over the next 3 days, and when this minimum release will be reached.

The rules and views presented are not necessarily the rules and views accepted by USACE or other government agencies—current USACE policy is to not use forecast information or information from outside agencies, due to the possibility of communication blackout during an event. Further, although the NWS CNRFC conducts quality control of its forecasts, the USACE has no control over the product.

These hurdles remain and must be overcome before the proposed forecast rules can be put into practice. Successful forecast-based operation depends on the stakeholders' and sponsors' willingness to use forecast information and to make releases greater than inflow based on this forecast information. The solution lies somewhere between two extremes: the current policy without forecast-based releases and a policy which assumes forecasts are perfect. In addition, the optimal refill probability for the rule could be less than the current USACE objective of 99%. To optimize this non-linear problem, an acceptable level of risk based on forecast uncertainty must be agreed upon by balancing the expected cost of lost water supply, unnecessary early levee damage, and other impacts with the expected cost of flood damages and life loss if levees fail.

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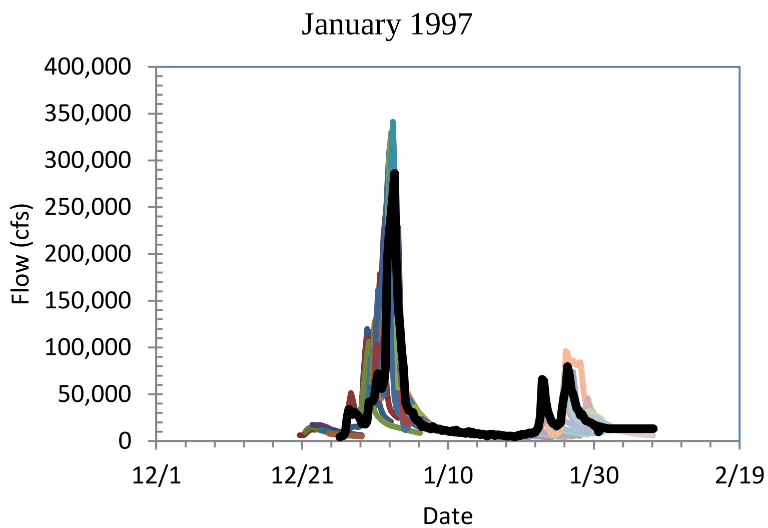
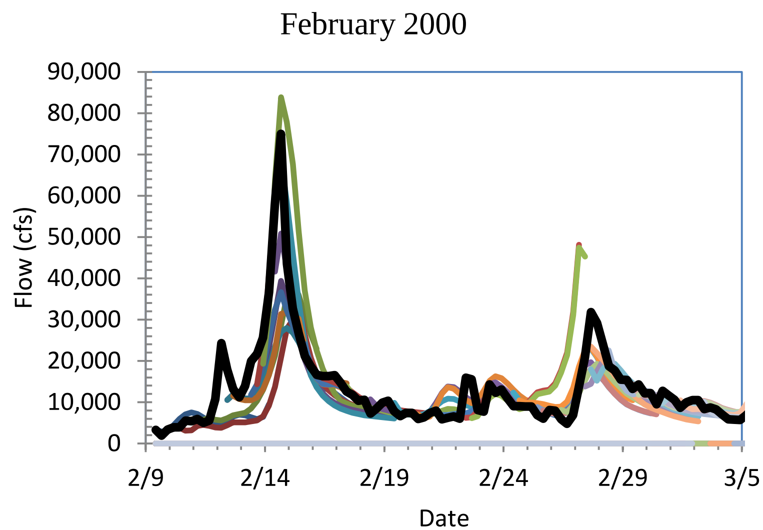
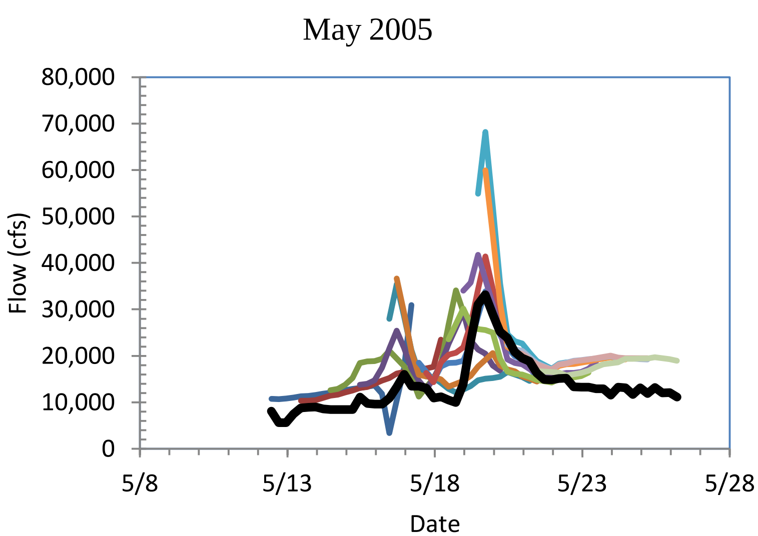
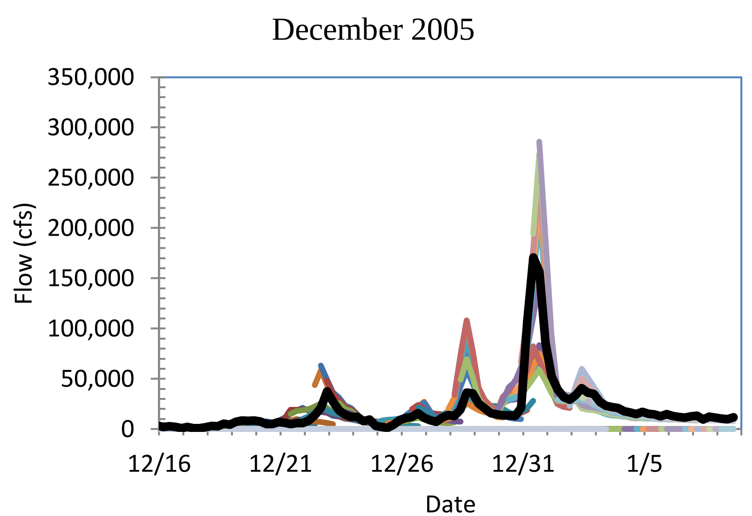
Appendix A. Flow Forecasts from Period of Record









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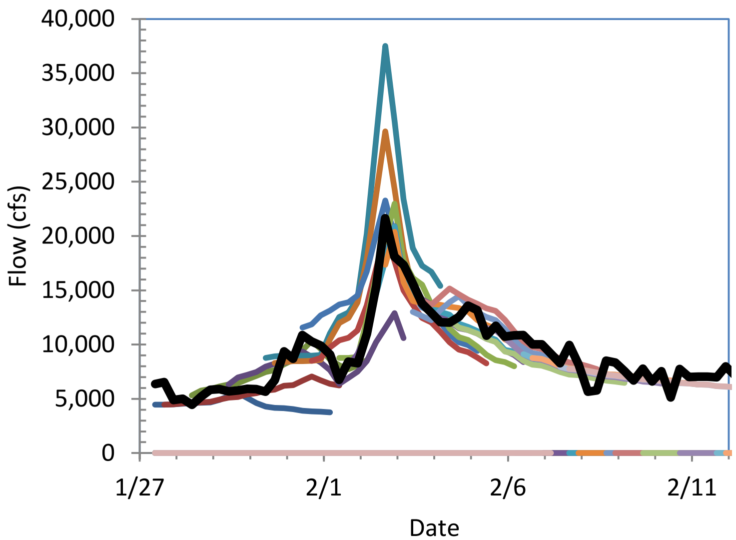

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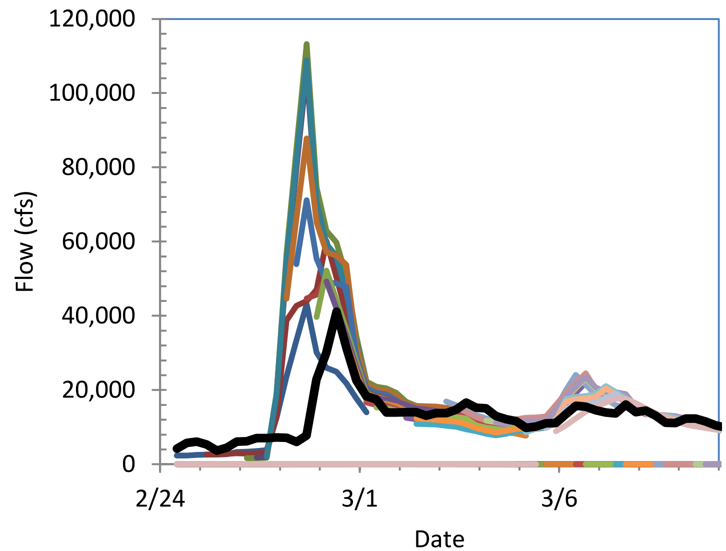
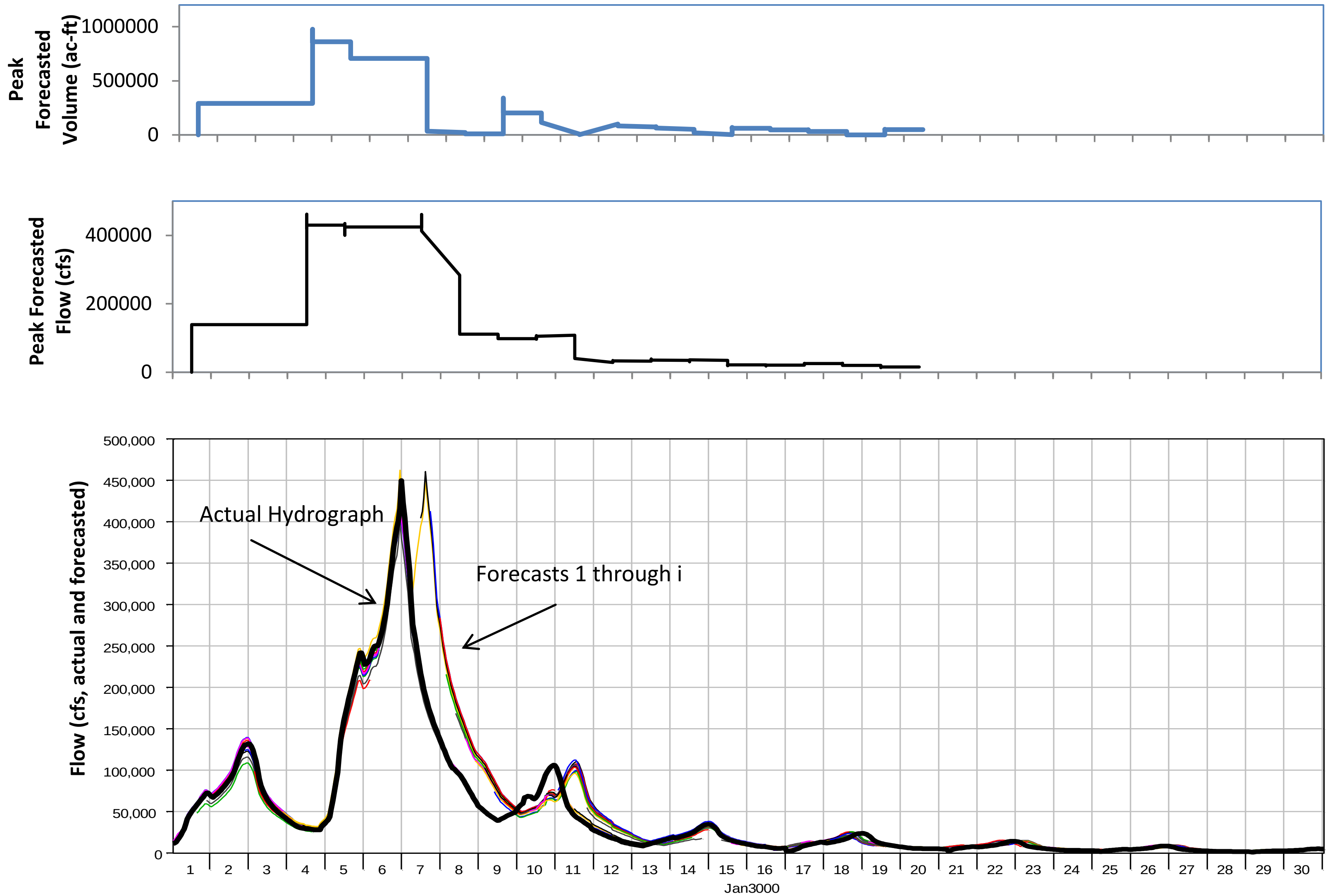
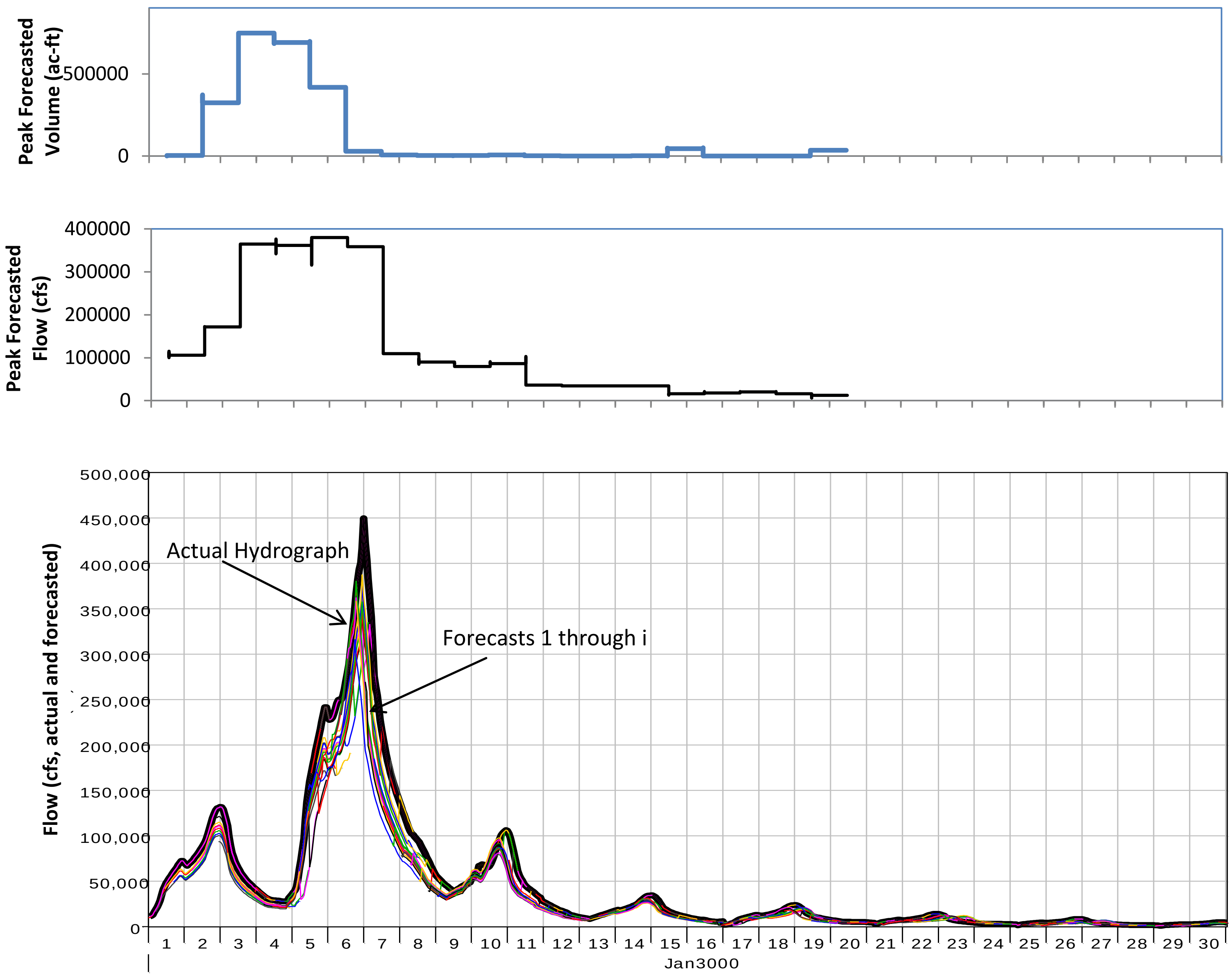


Appendix B. Forecast Shapes and Corresponding Artificial Forecasts

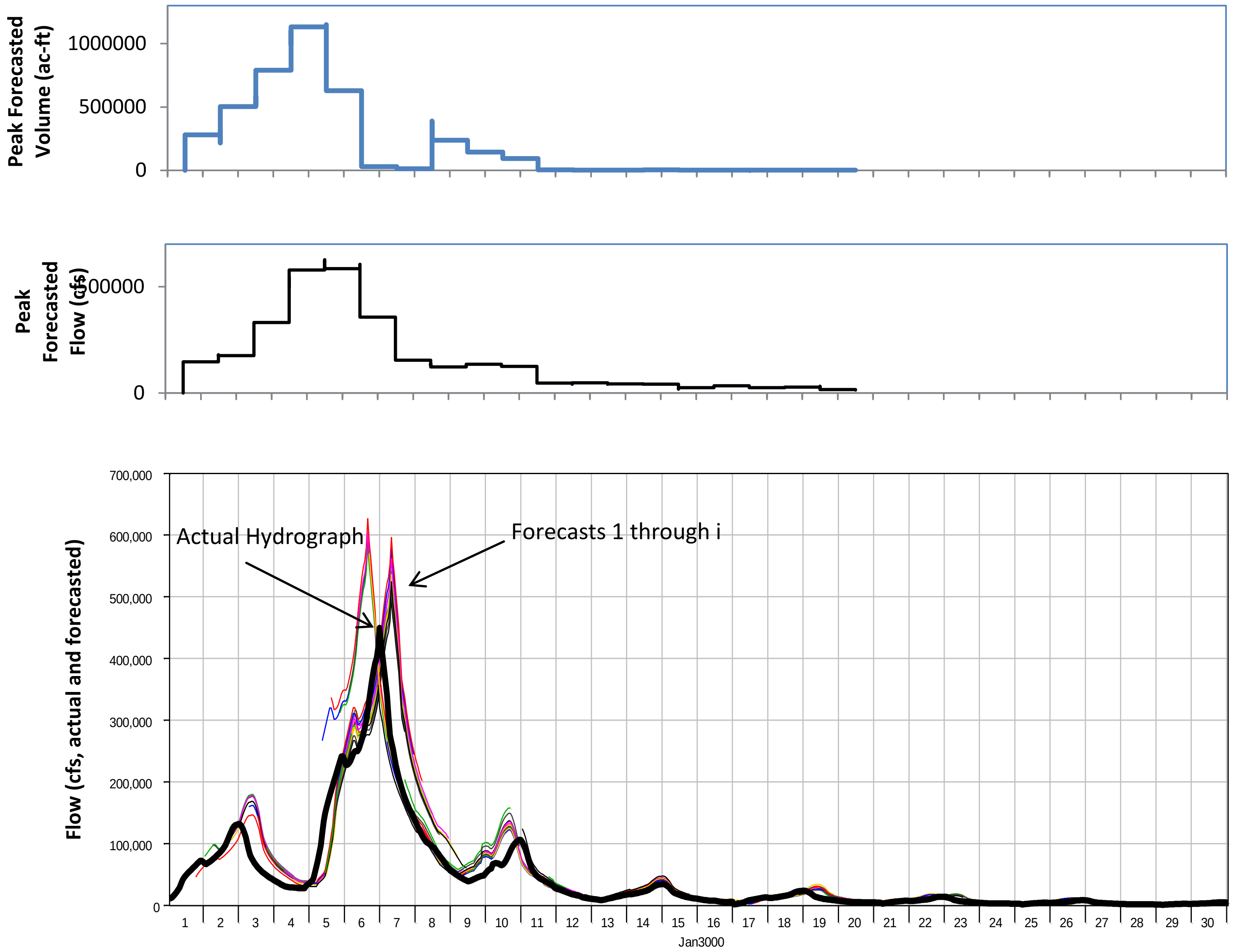
PMF Forecasts and 3-day summaries (actual hydrograph in bold)
On Time Forecast (PMF Shape, 200-year)



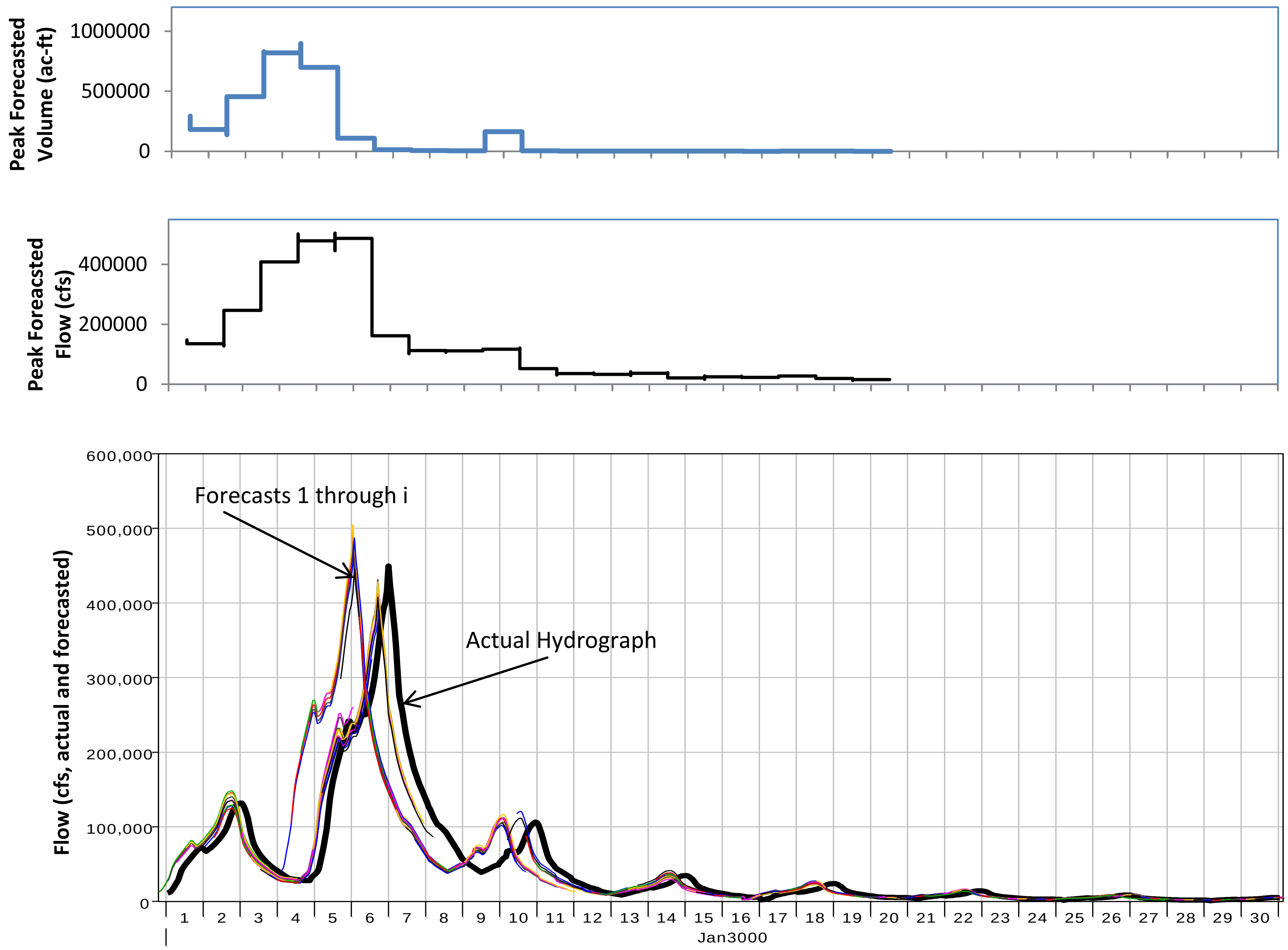
Low Forecast (PMF Shape, 200-year)



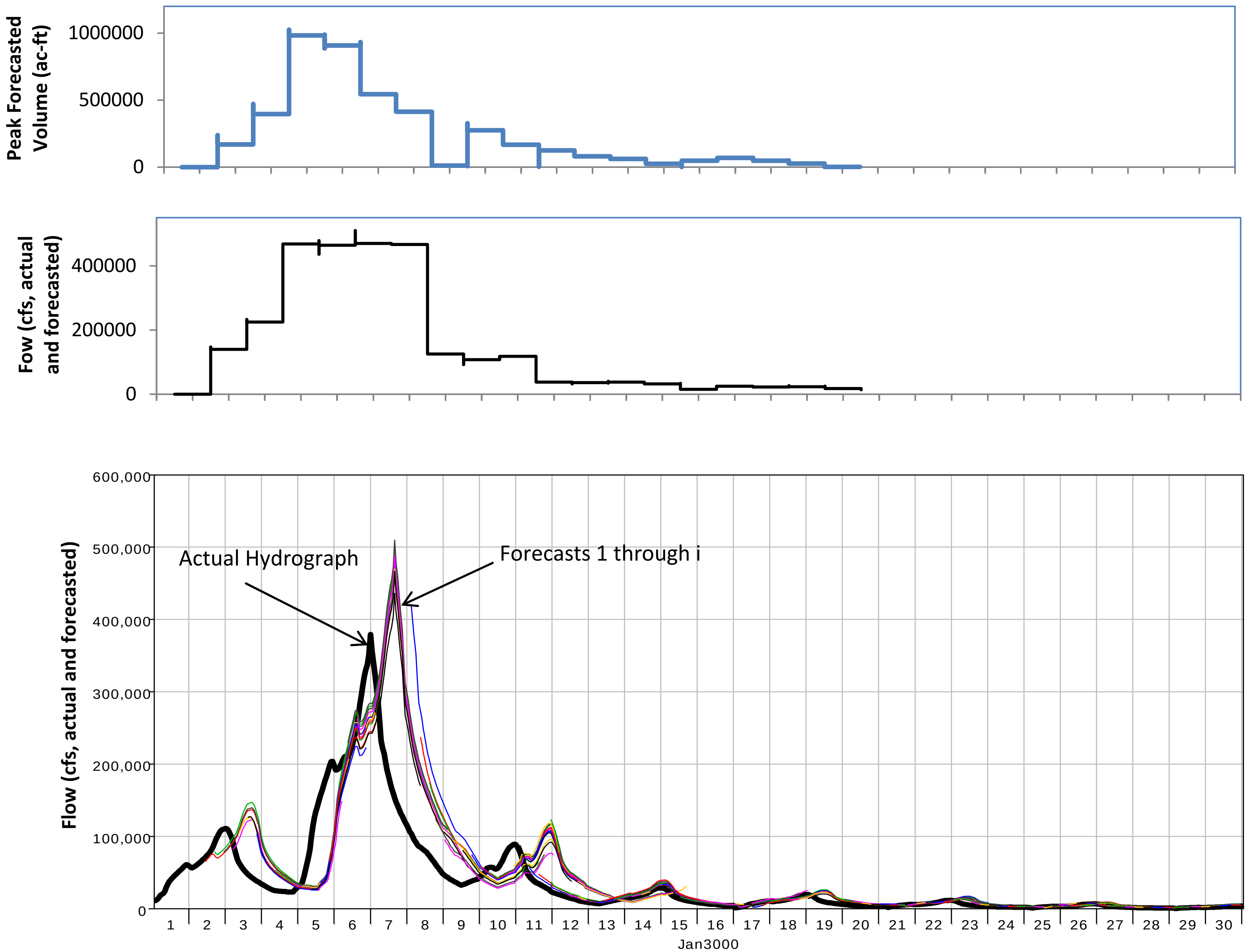
High Forecast (PMF Shape, 200-year)



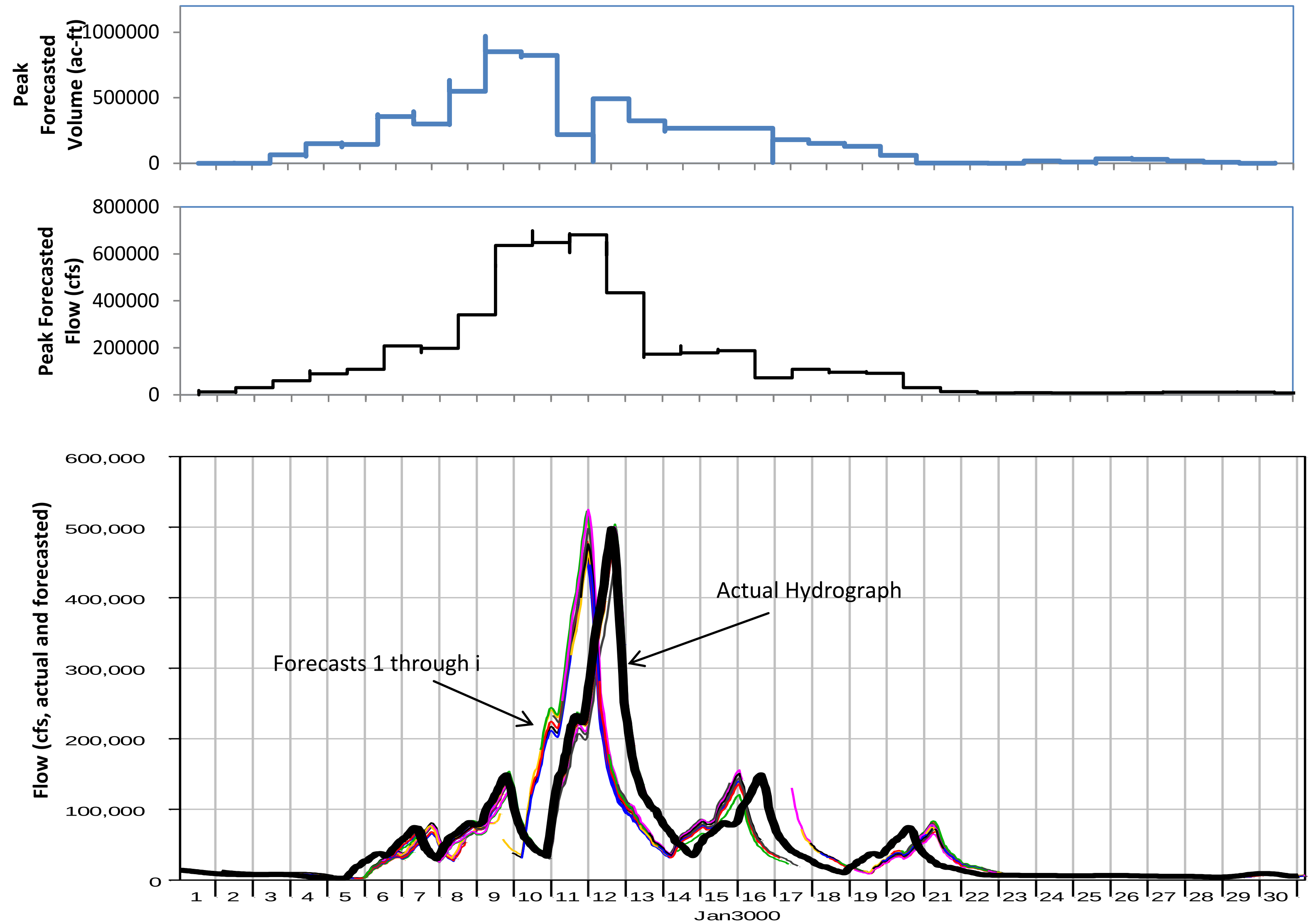
Early Forecast (PMF Shape, 200-year)



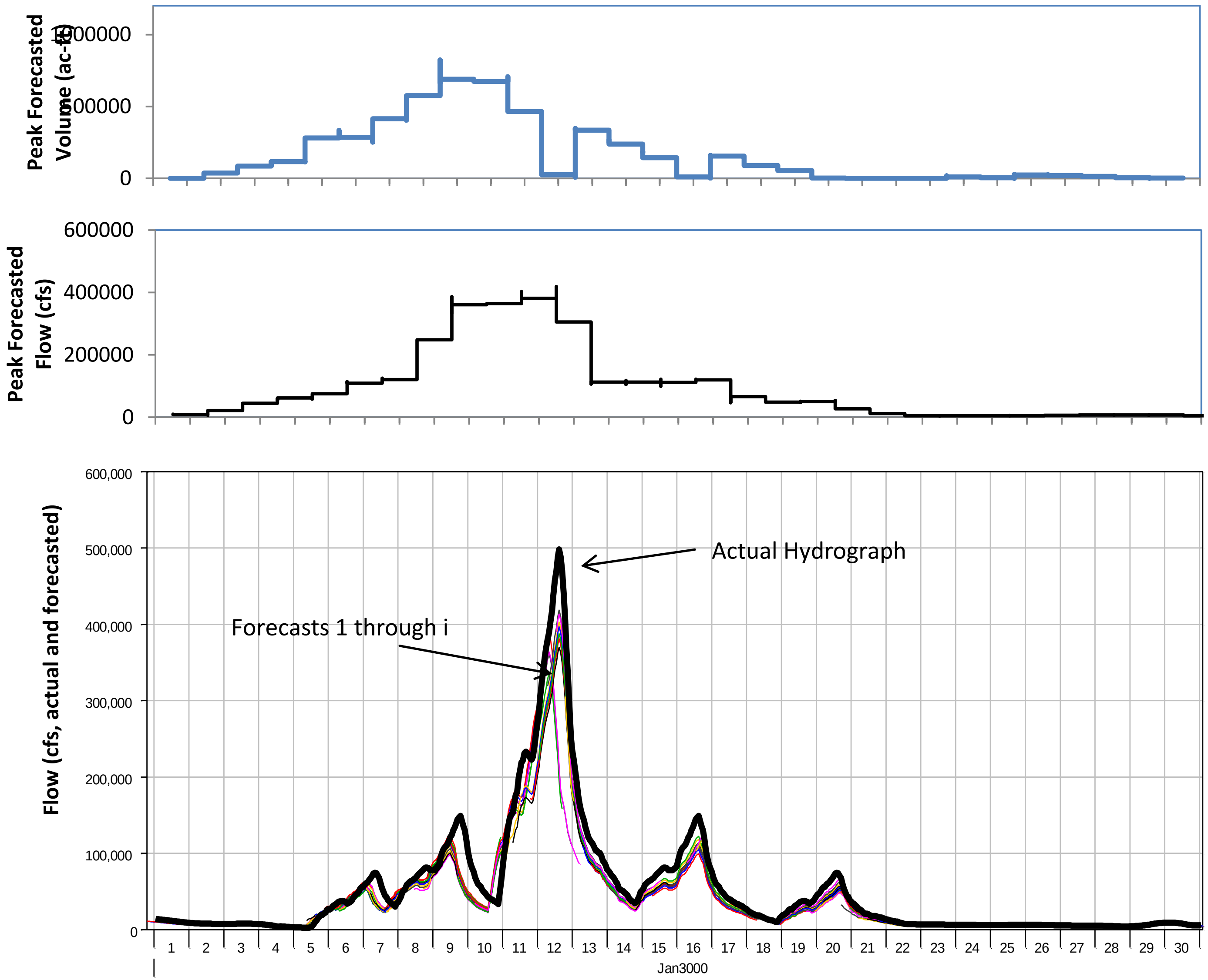
Late Forecast (PMF Shape, 200-year)



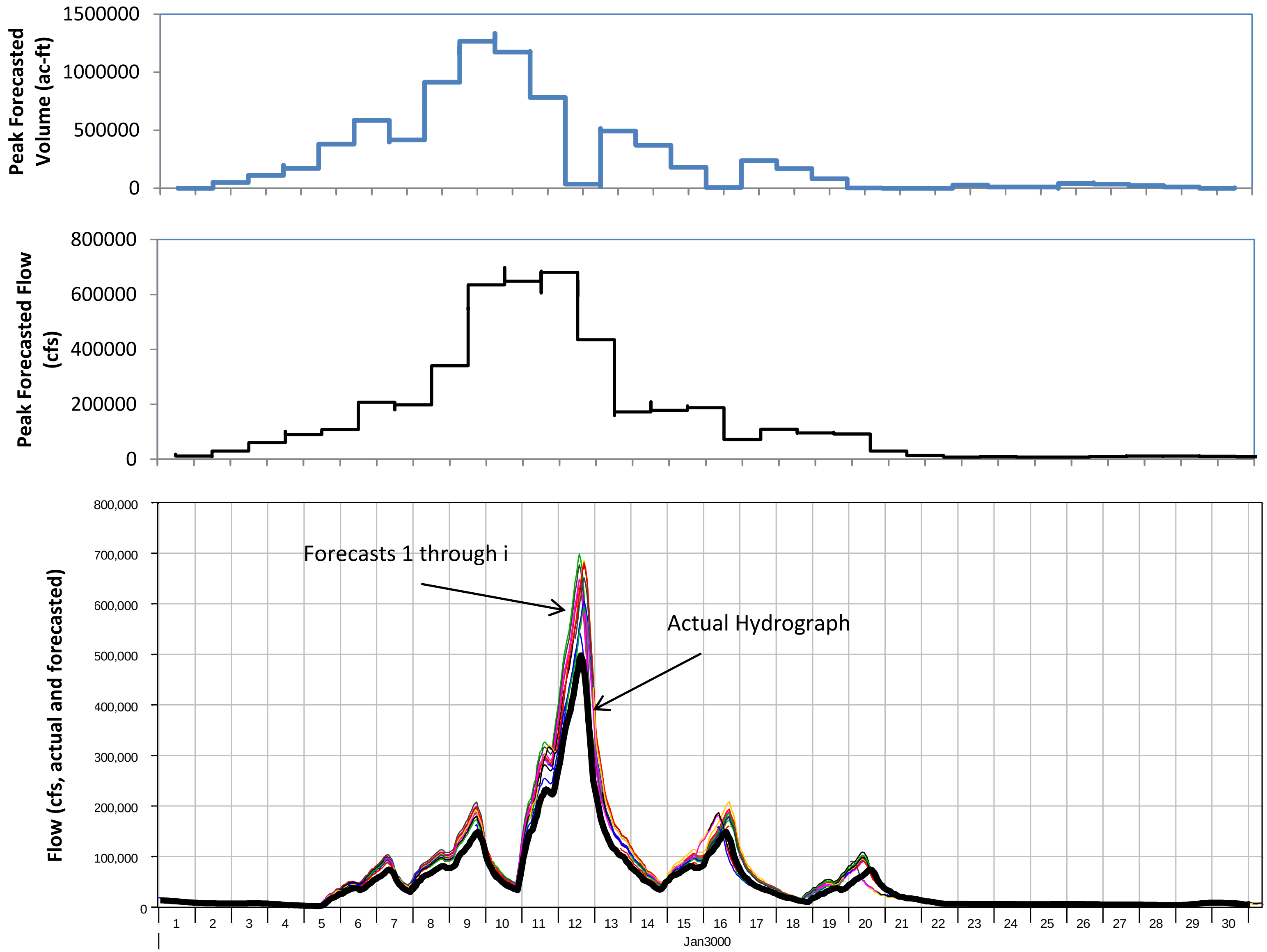
SPF Forecasts and 3-day summaries (actual hydrograph in bold)
On Time Forecast (SPF Shape, 200-year)



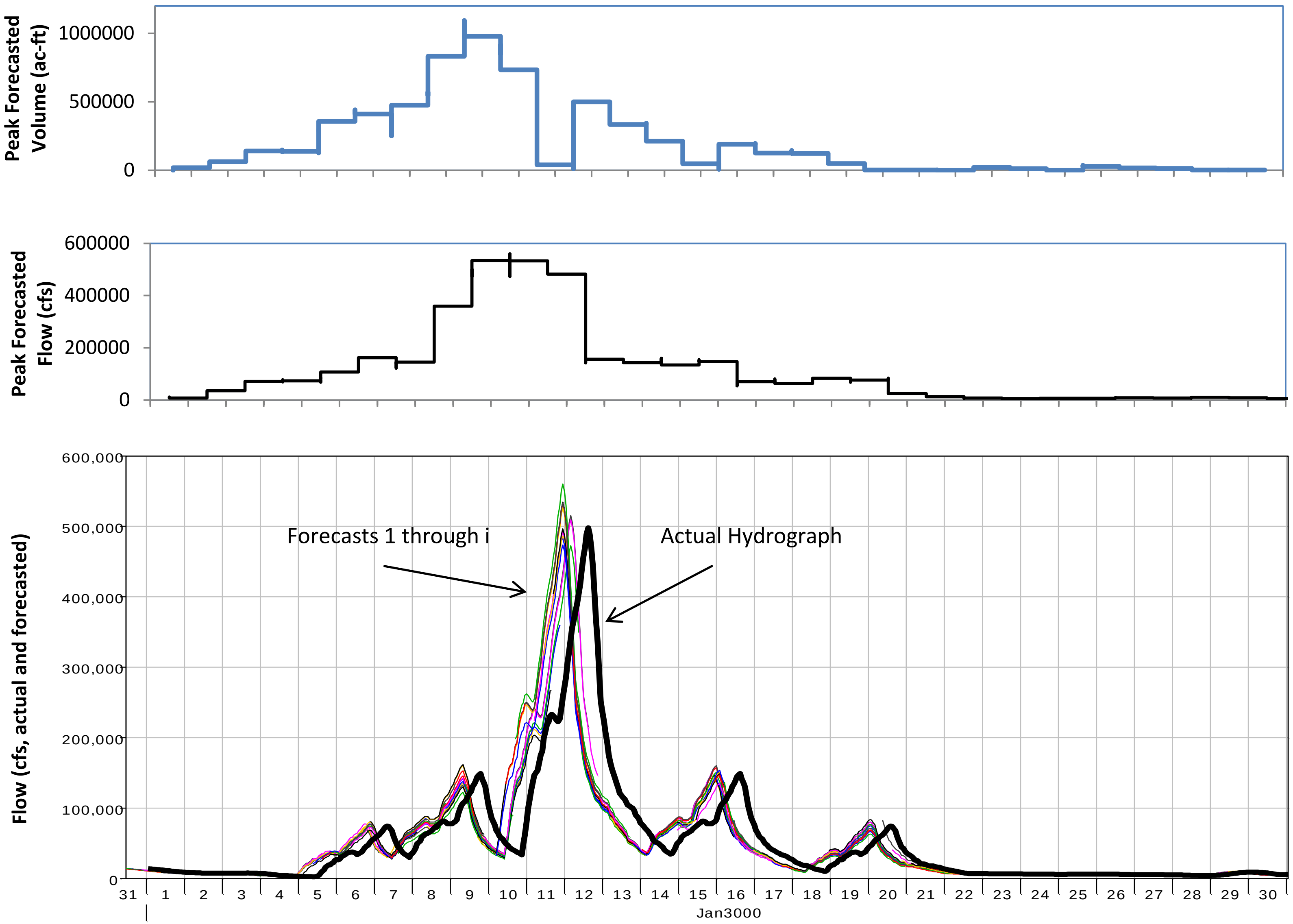
Low Forecast (SPF Shape, 200-year)



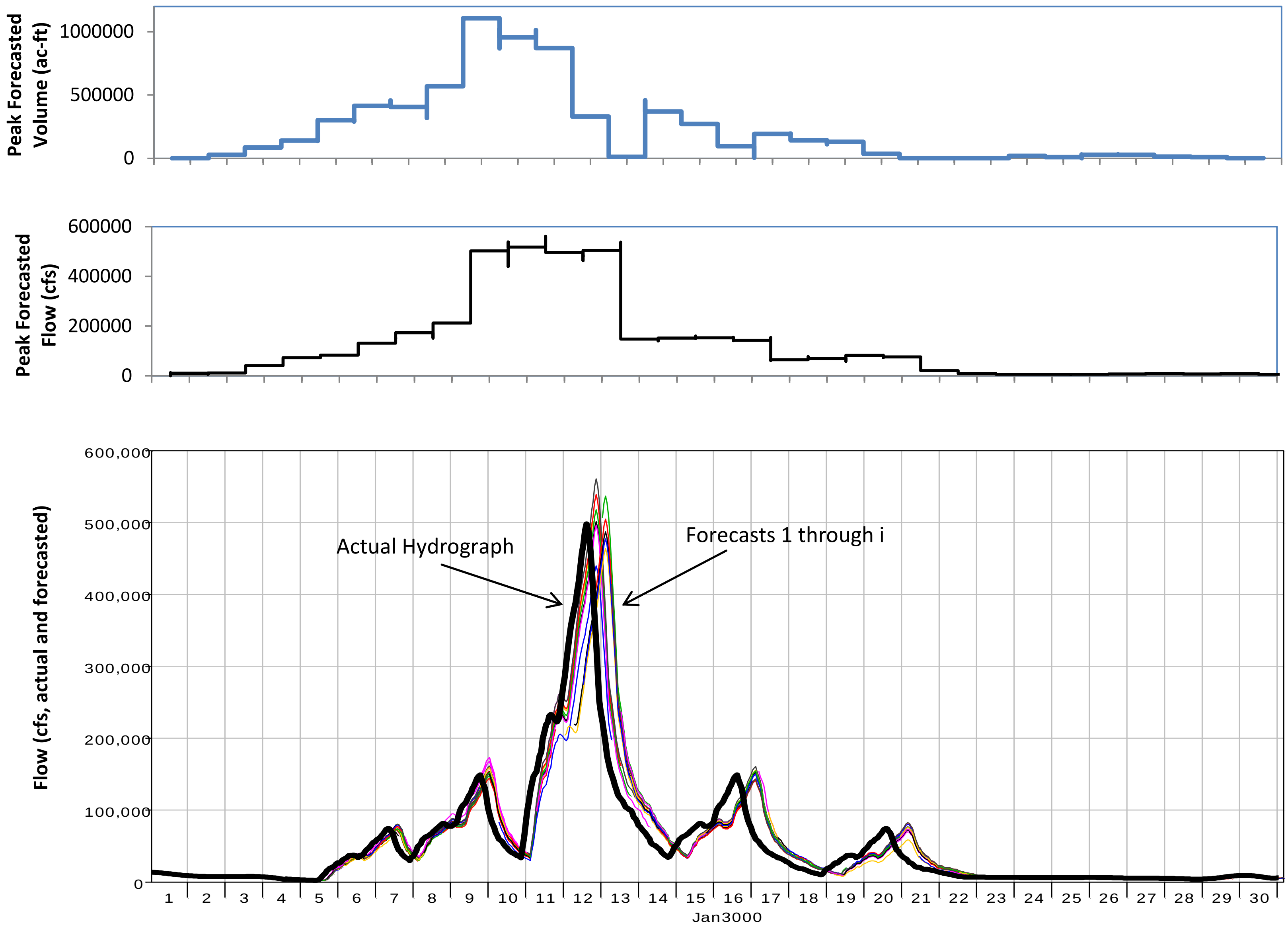
High Forecast (SPF Shape, 200-year)



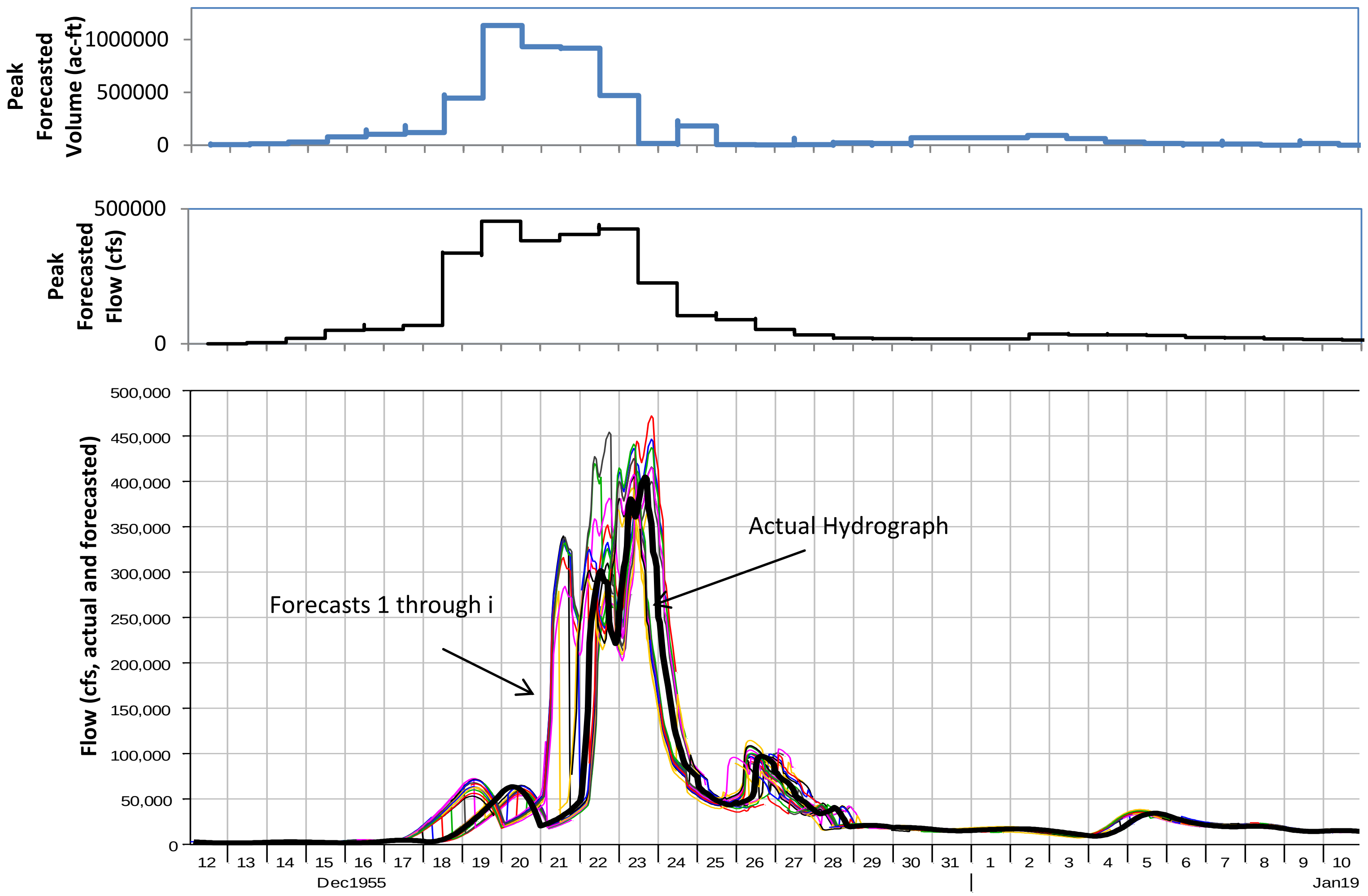
Early Forecast (SPF Shape, 200-year)



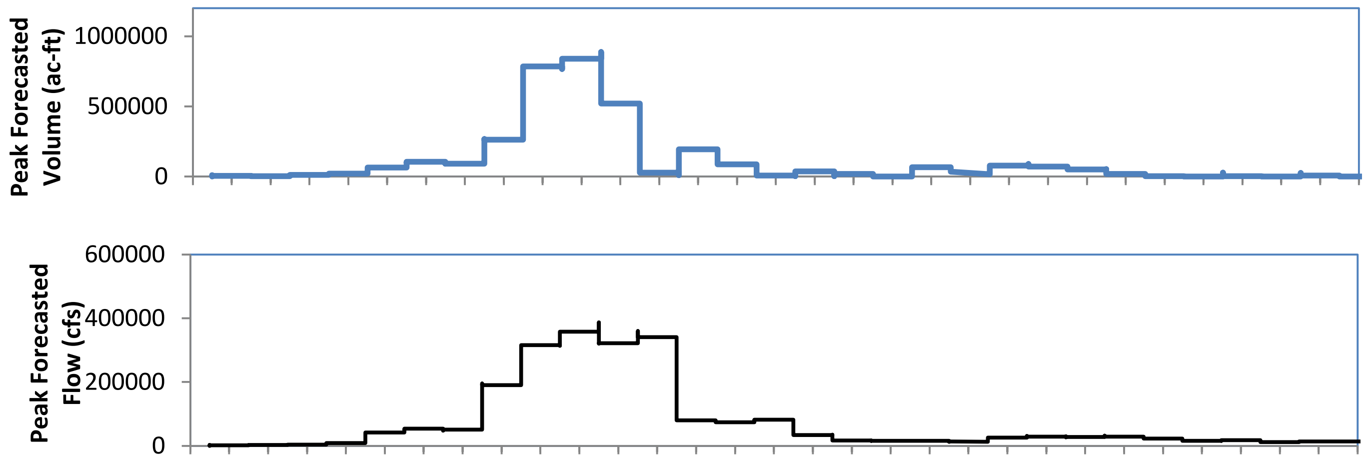
Late Forecast (SPF Shape, 200-year)

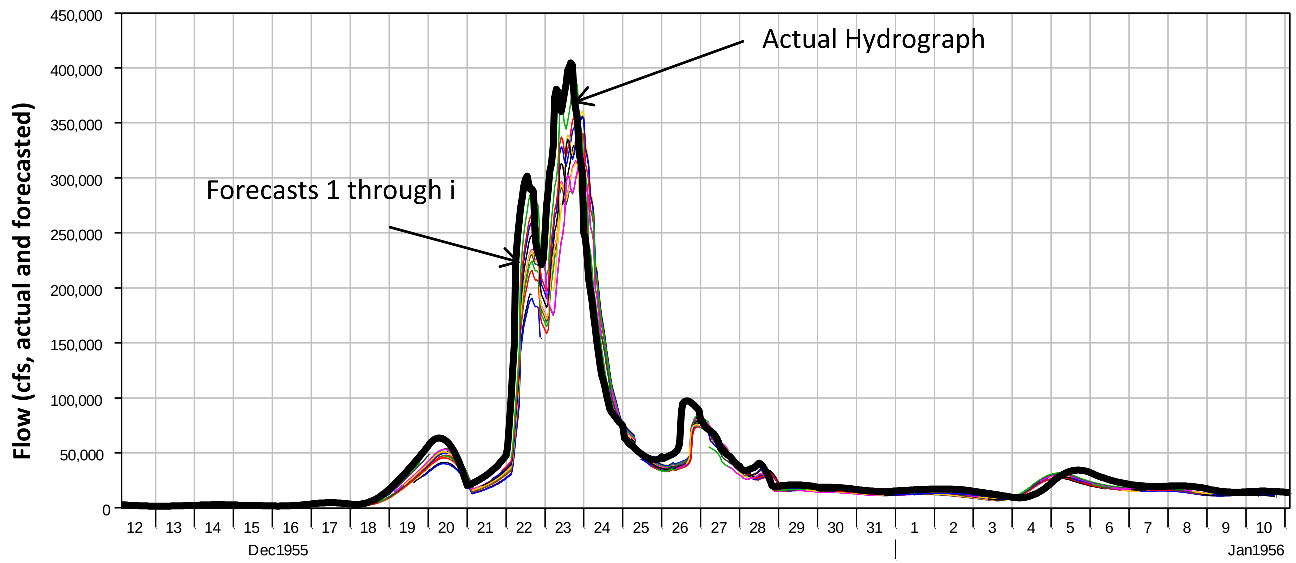


1955 Forecasts and 3-day summaries (actual hydrograph in bold)
On Time Forecast (1955 Shape, 200-year)

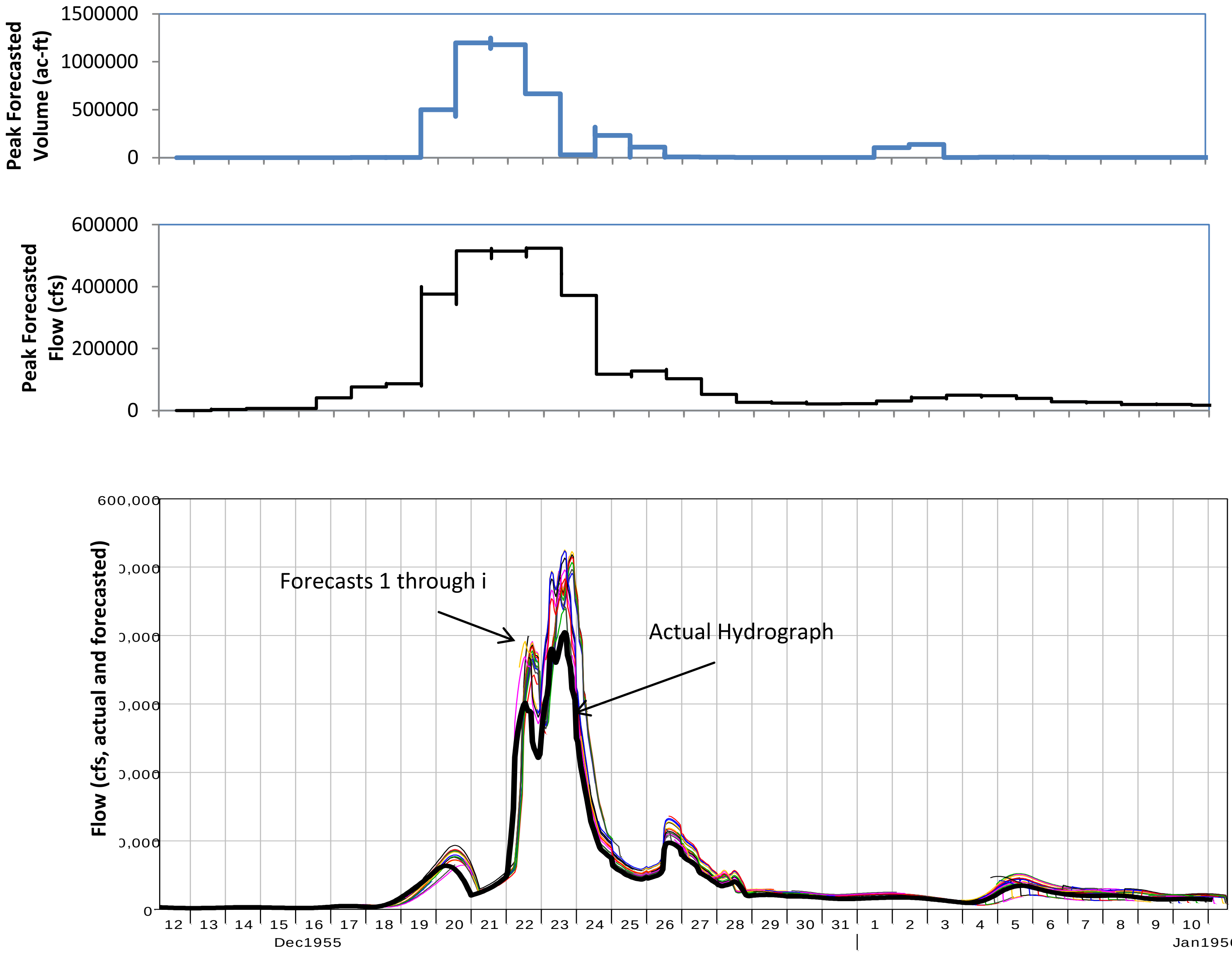


Low Forecast (1955 Shape, 200-year)

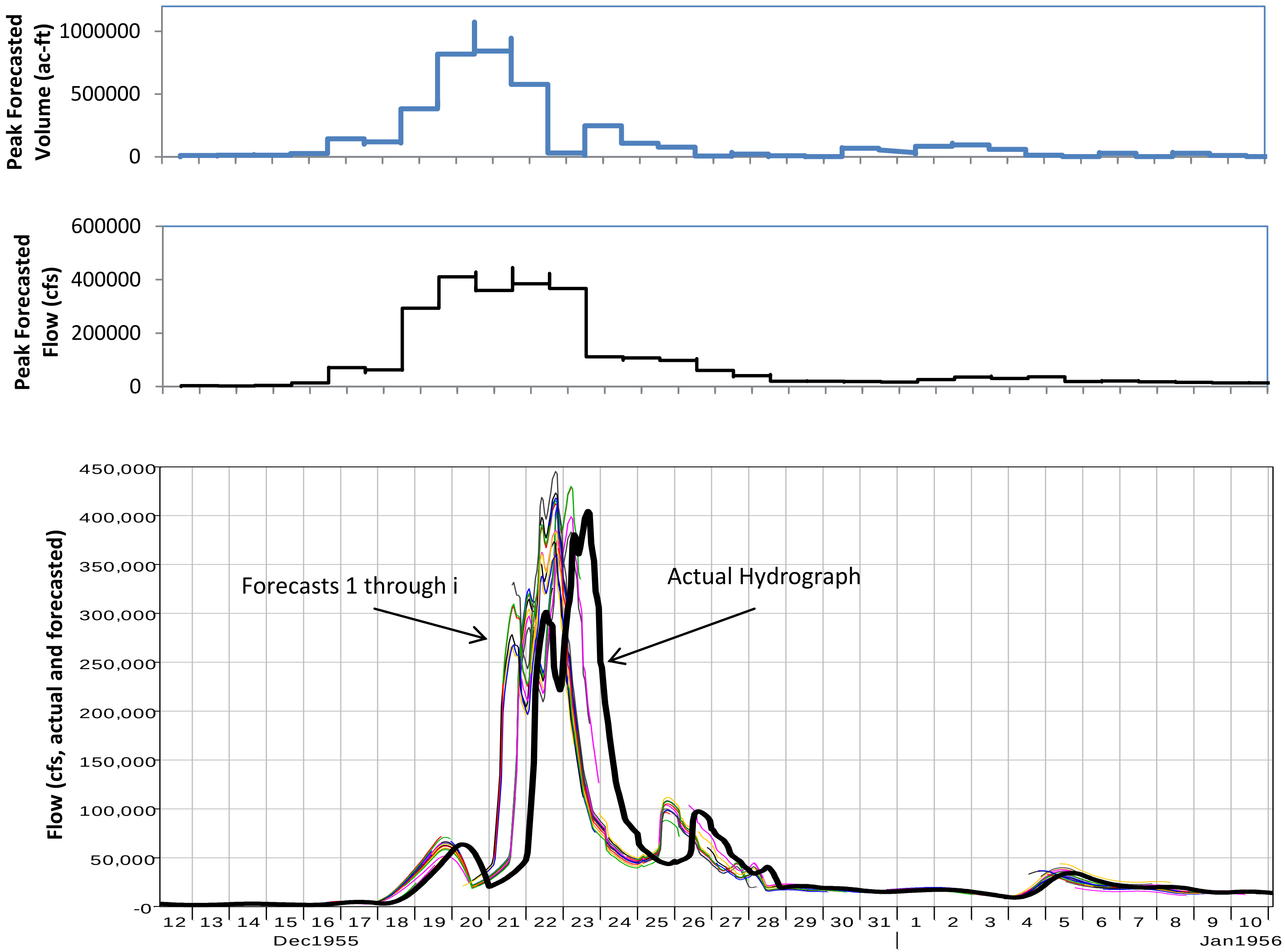




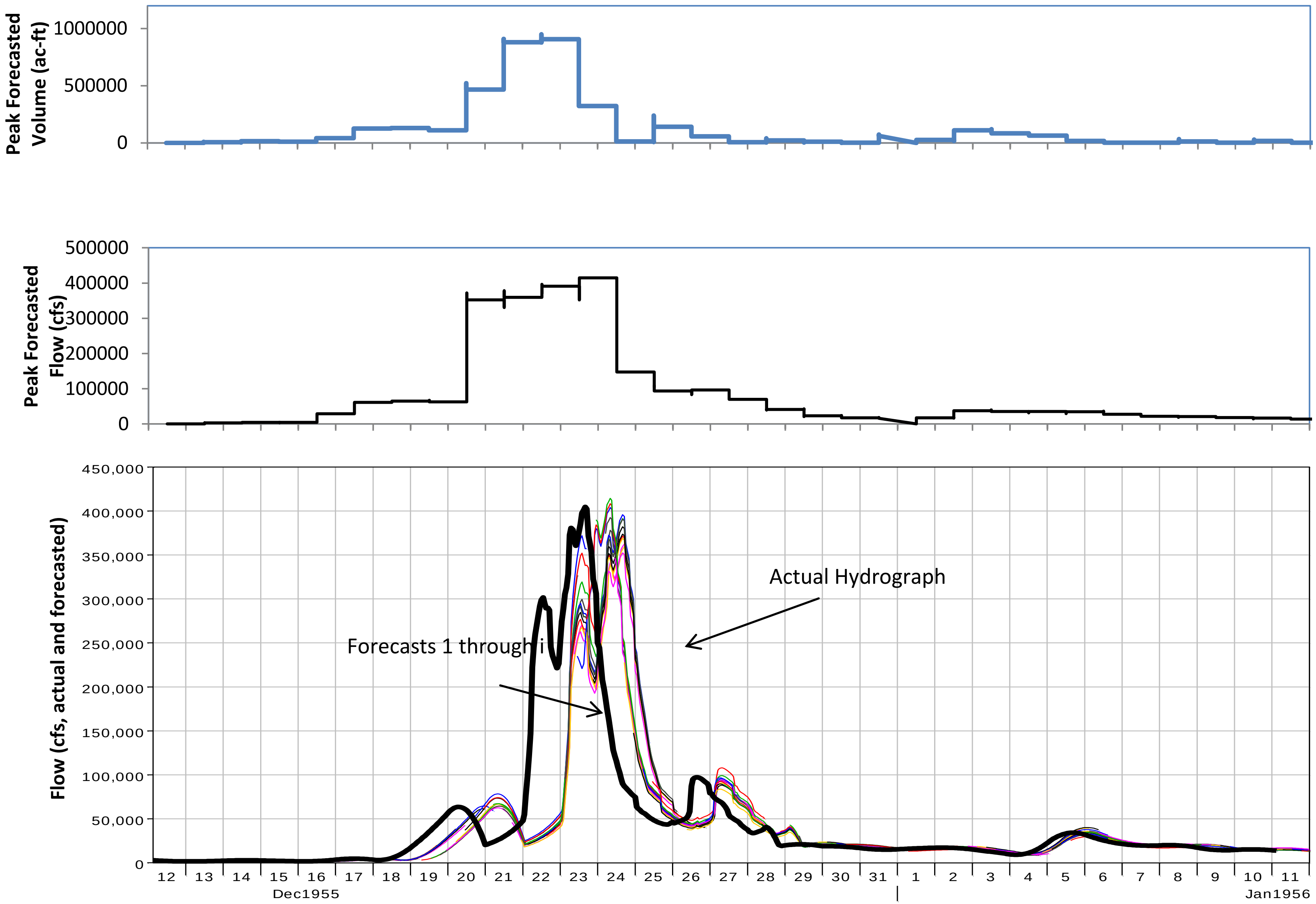
High Forecast (1955 Shape, 200-year)



Early Forecast (1955 Shape, 200-year)

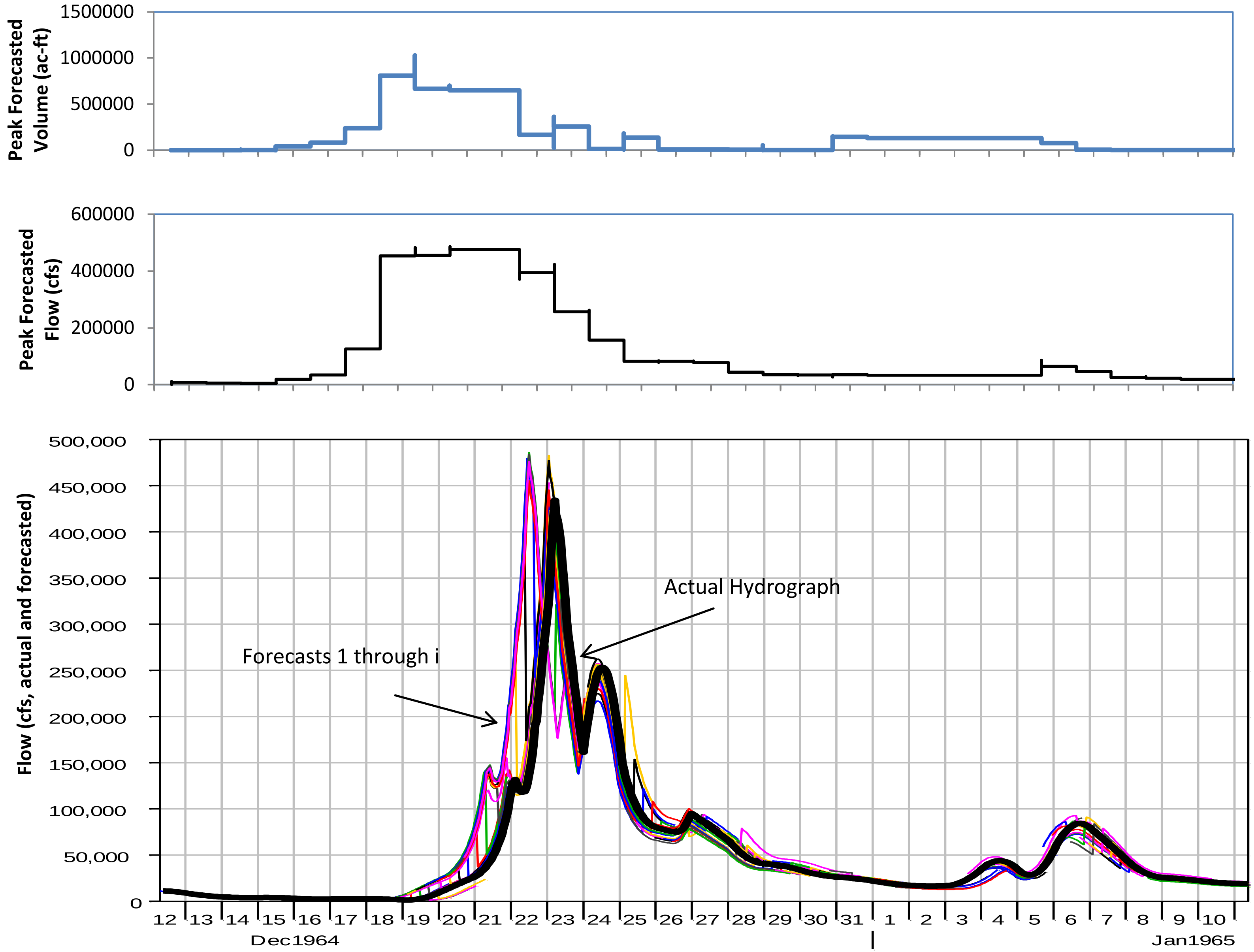


Late Forecast (1955 Shape, 200-year)

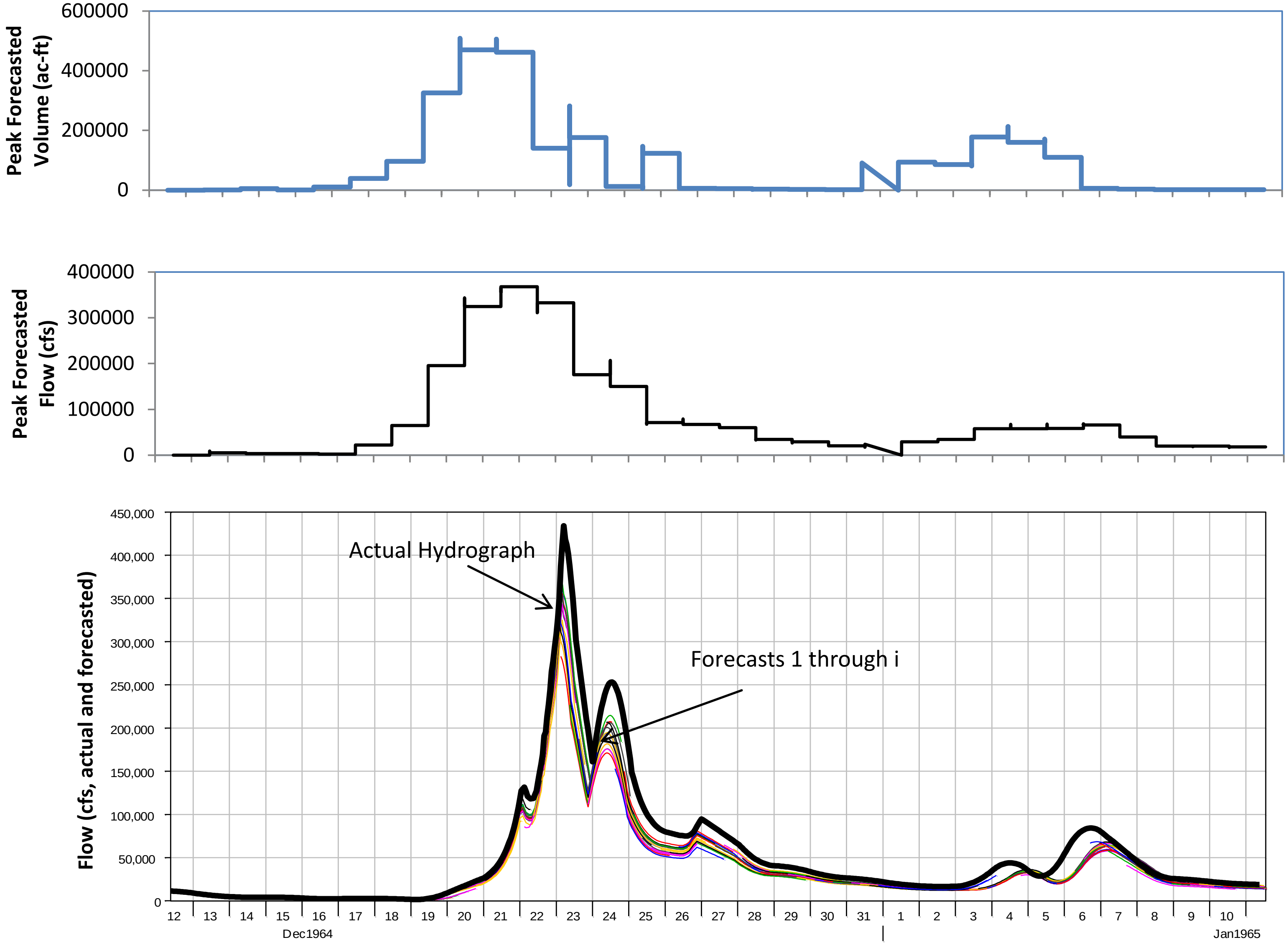


1964 Forecasts and 3-day summaries (actual hydrograph in bold)

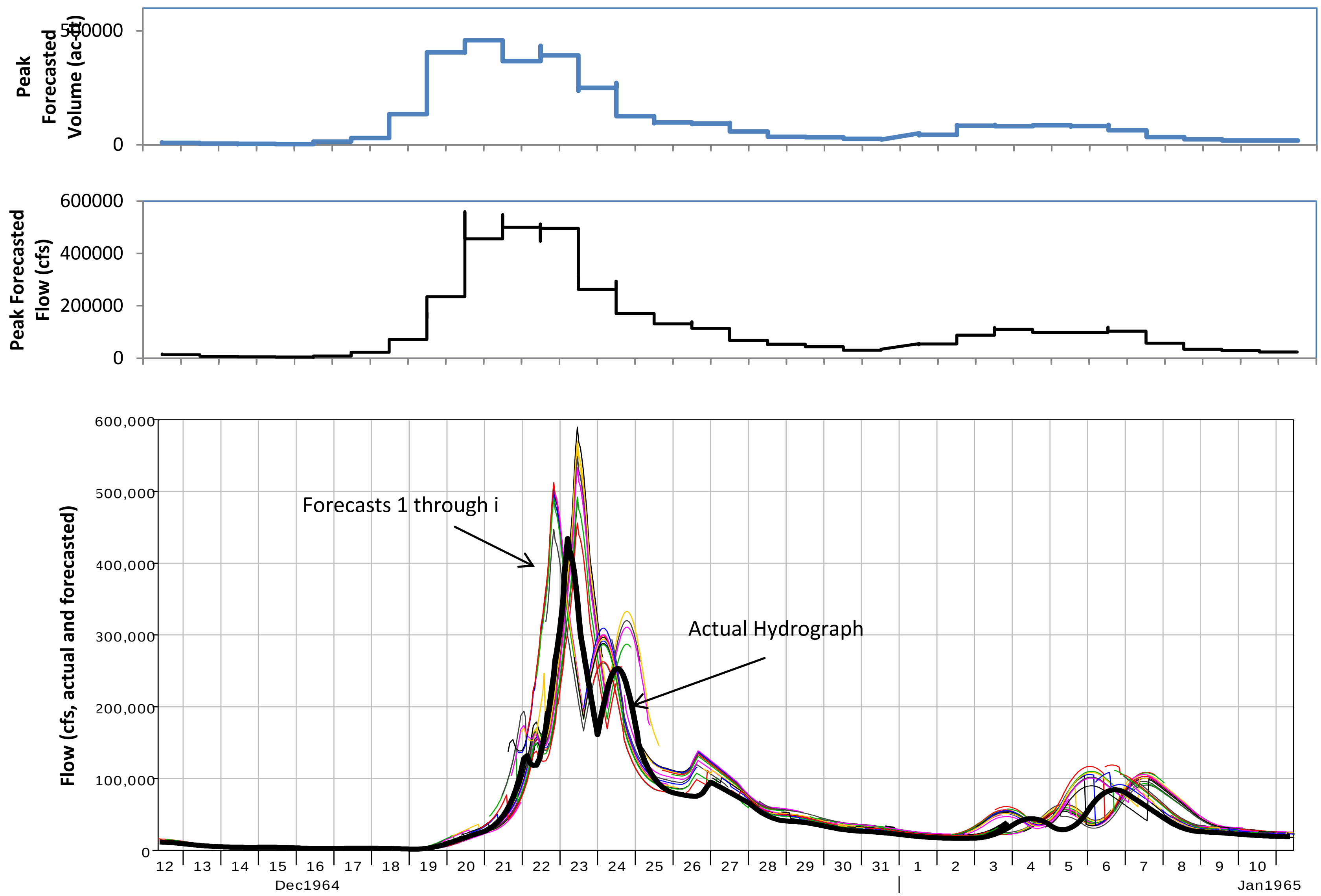
On Time Forecast (1964 Shape, 200-year)



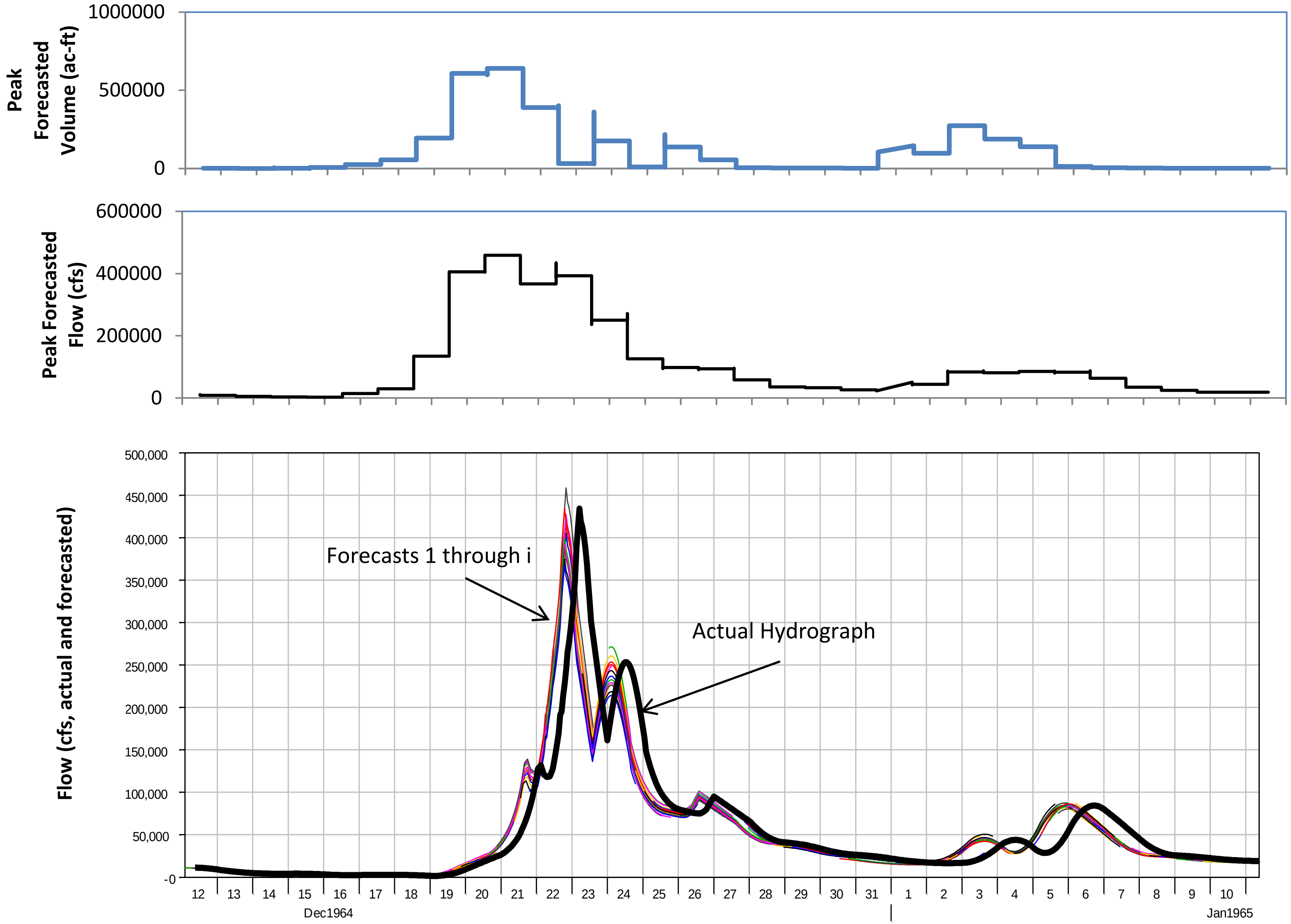
Low Forecast (1964 Shape, 200-year)



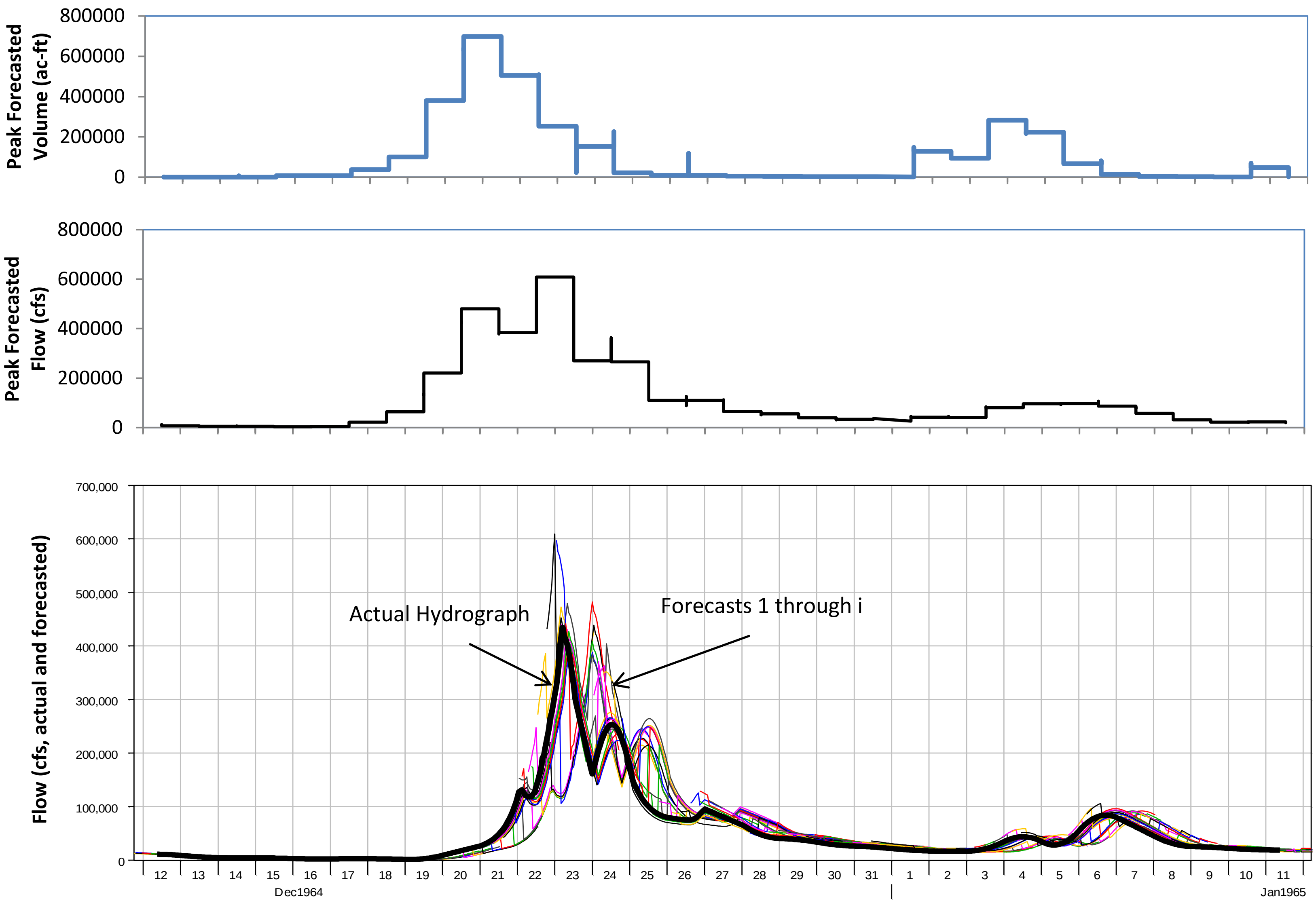
High Forecast (1964 Shape, 200-year)

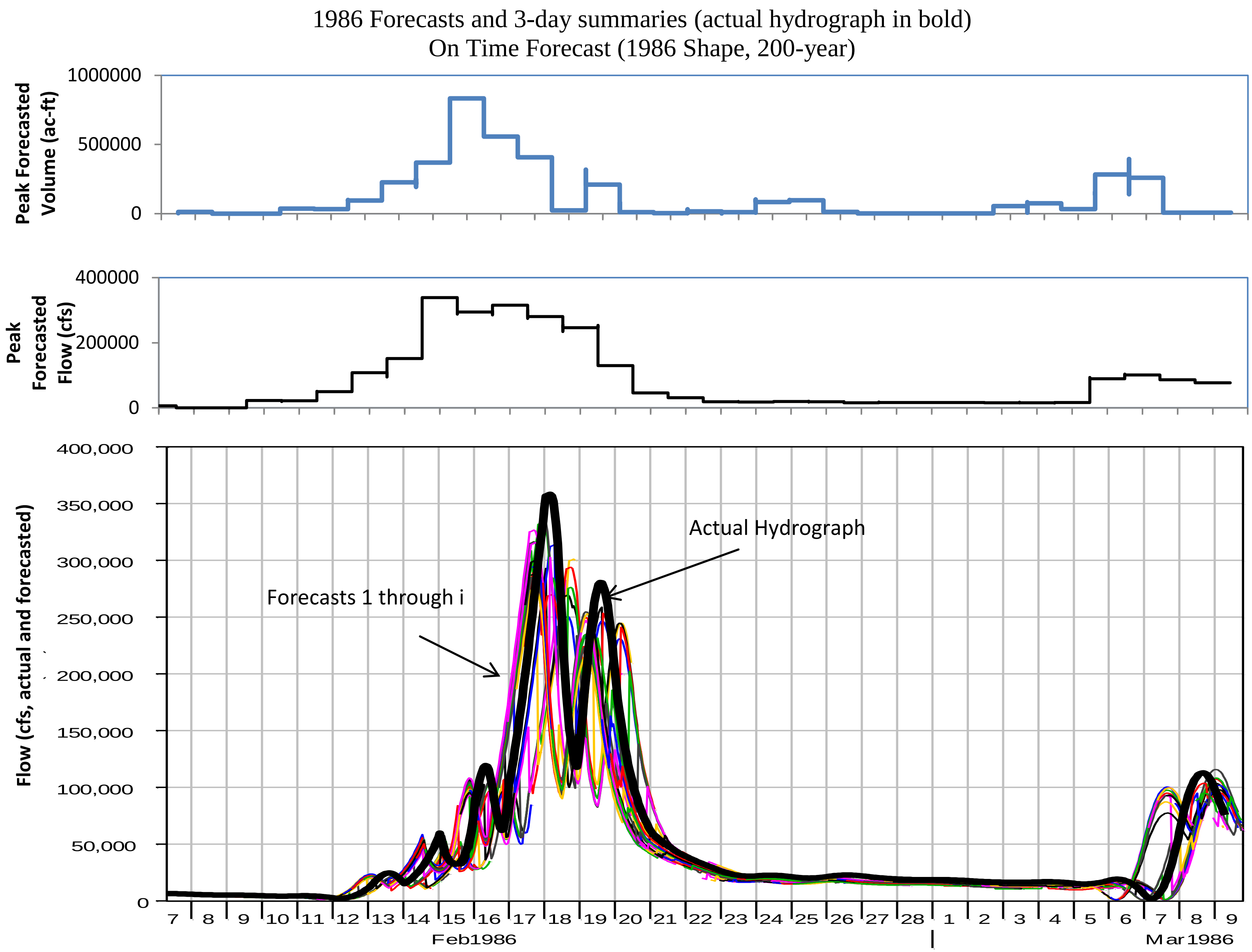


Early Forecast (1964 Shape, 200-year)

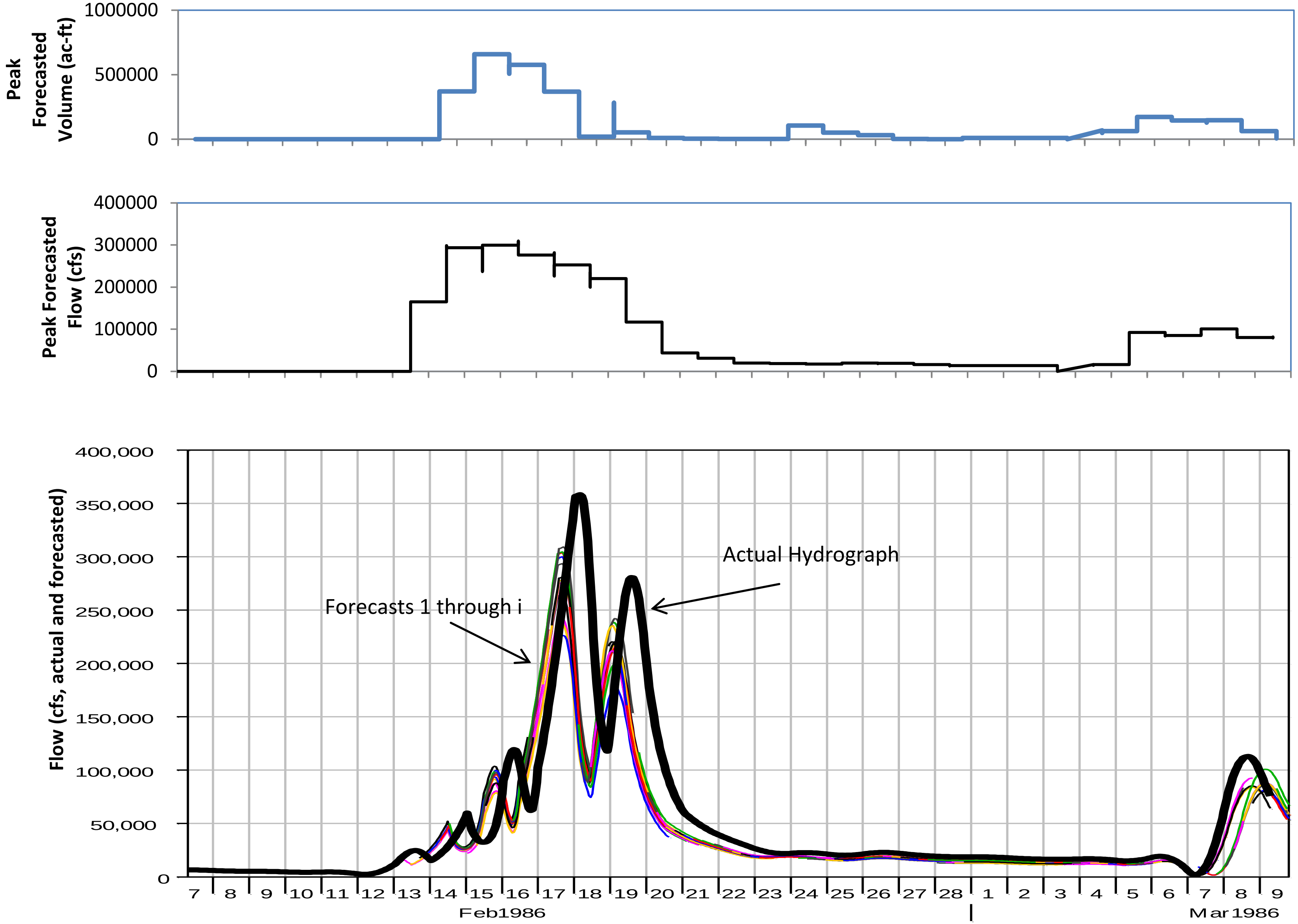


Late Forecast (1964 Shape, 200-year)

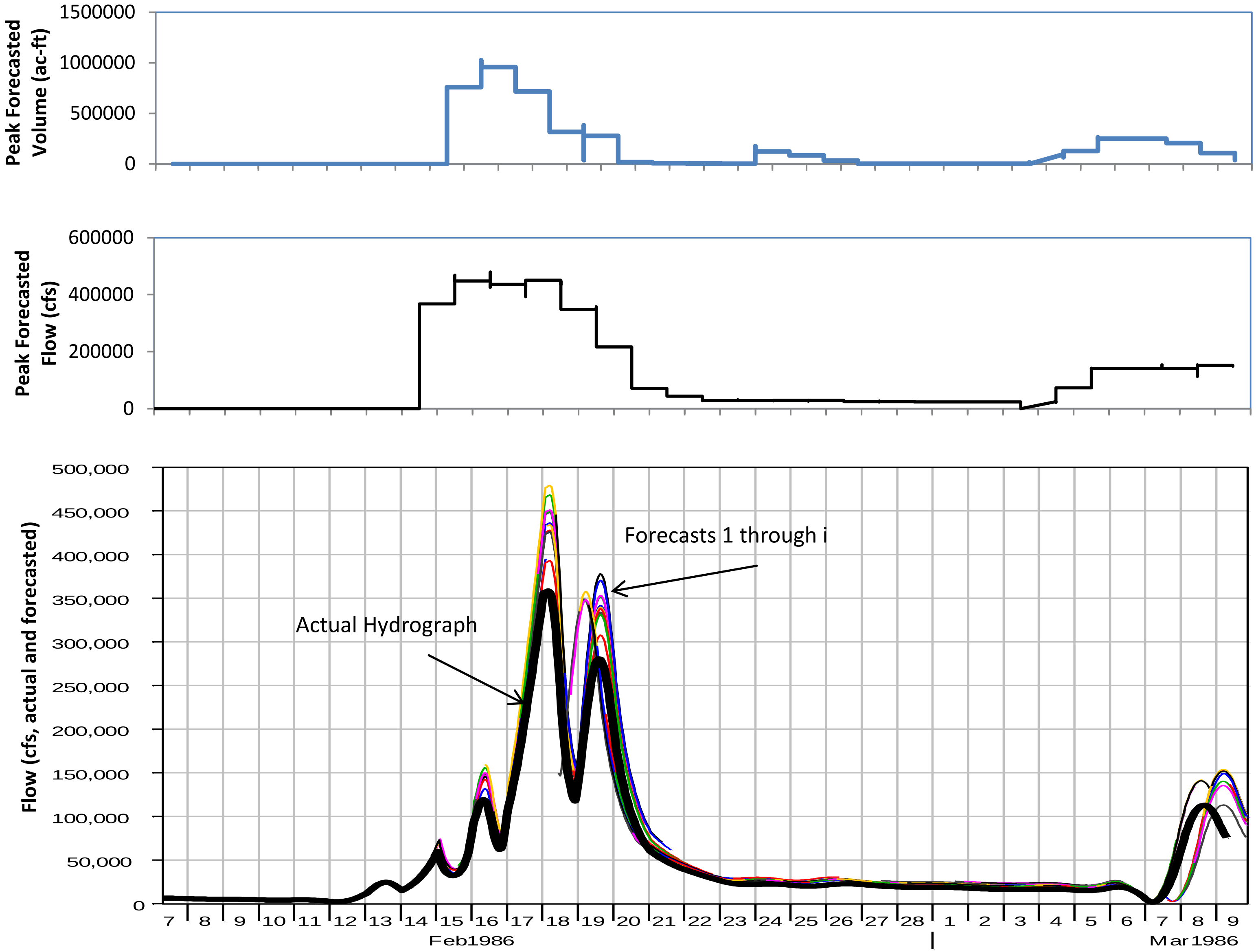



1986 Forecasts and 3-day summaries (actual hydrograph in bold)
On Time Forecast (1986 Shape, 200-year)
Peak Forecasted Volume (ac-ft)
1000000
500000
0
Peak Forecasted Flow (cfs)
400000
200000
0
Flow (cfs, actual and forecasted)
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
Actual Hydrograph
Forecasts 1 through i
7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 1 2 3 4 5 6 7 8 9
Feb1986
Mar1986

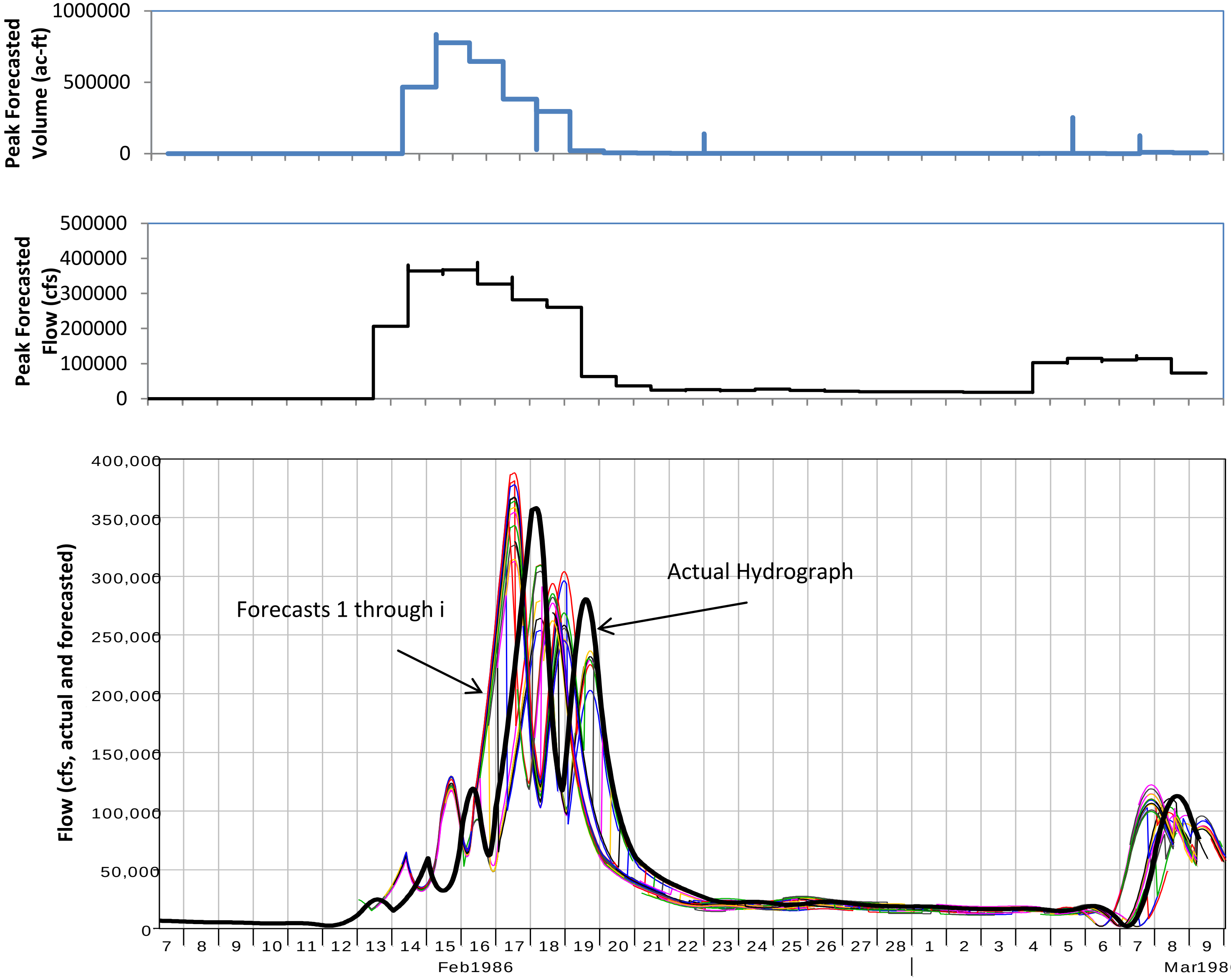
Low Forecast (1986 Shape, 200-year)



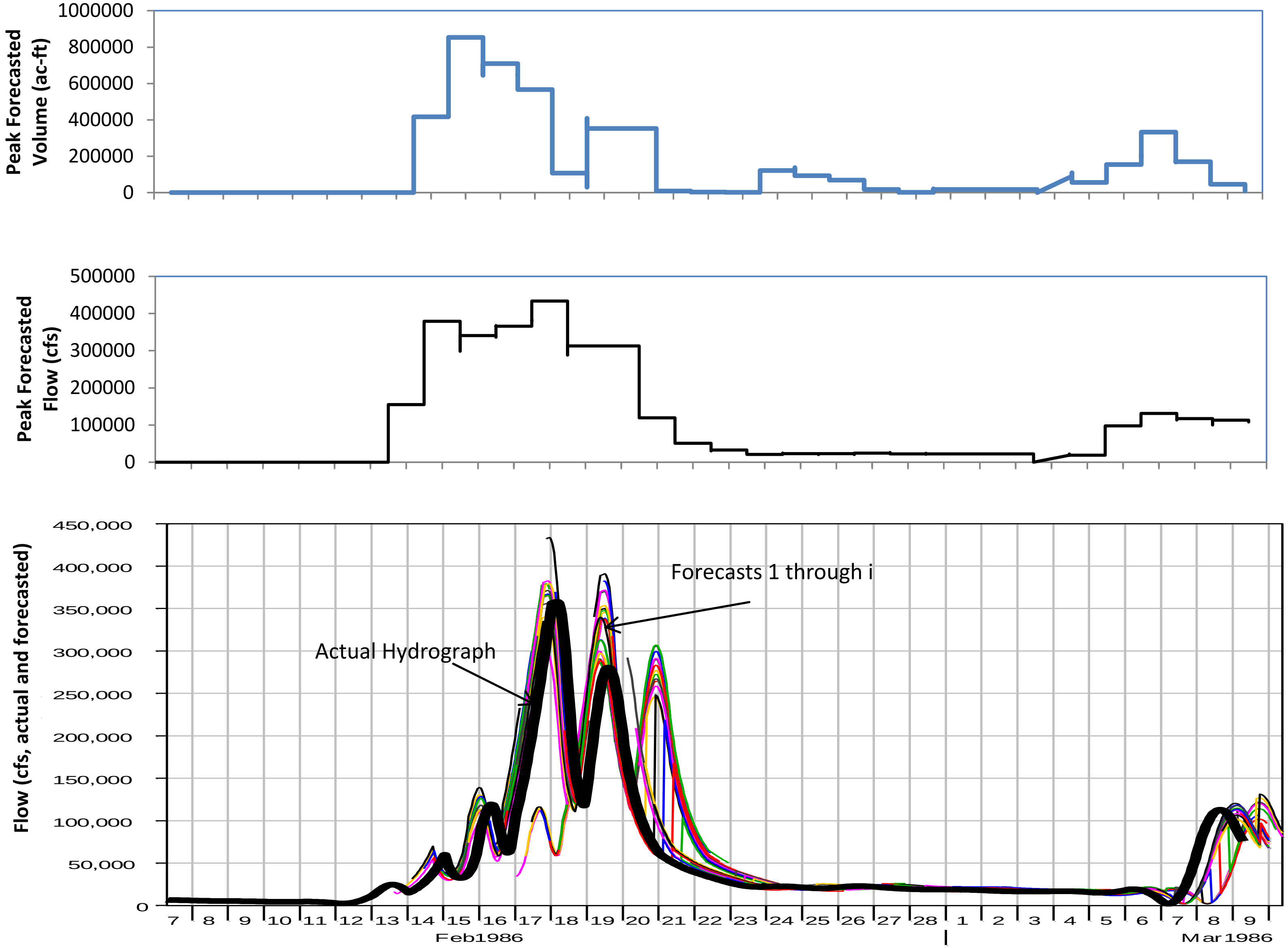
High Forecast (1986 Shape 200-year)



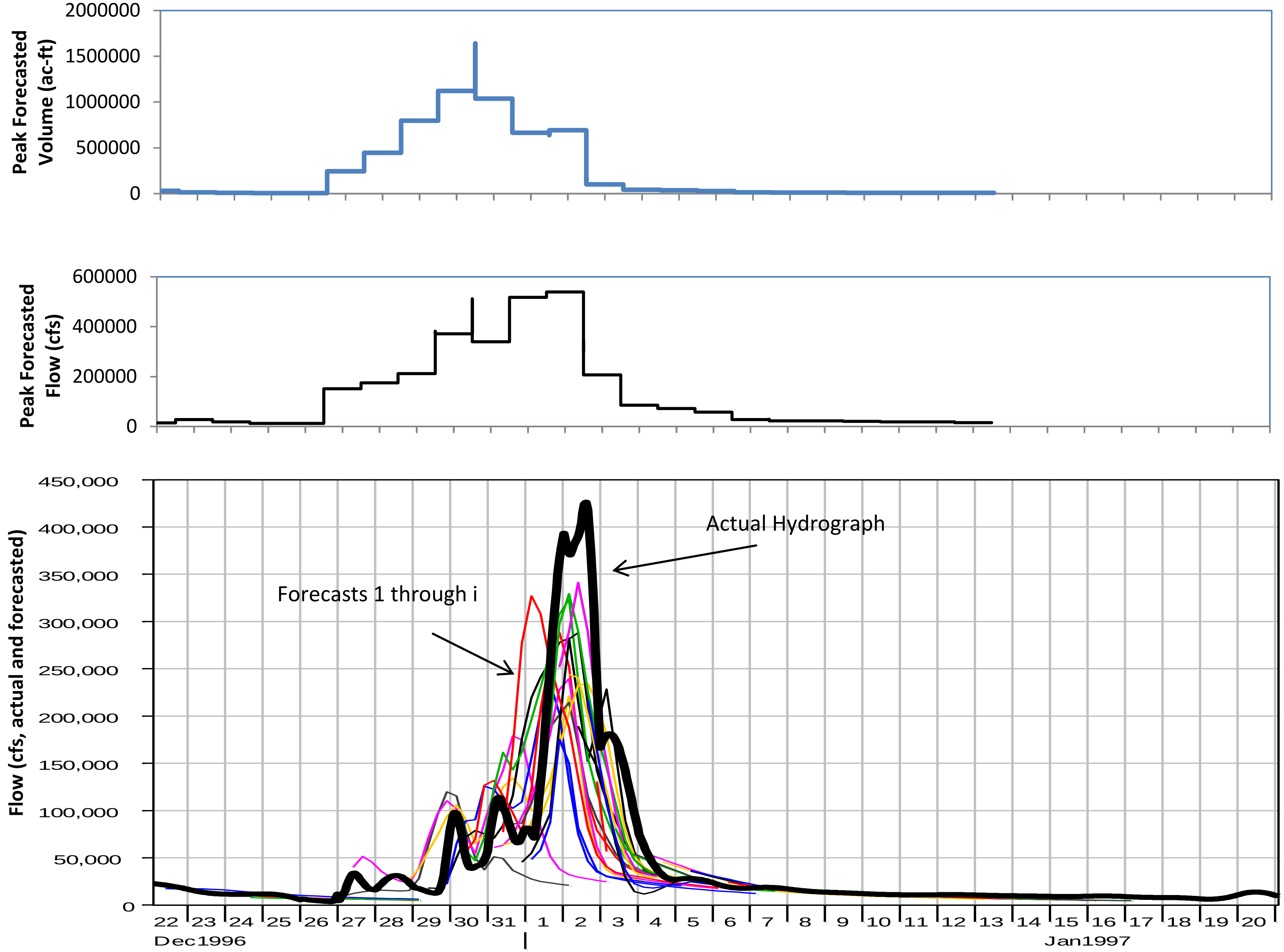
Early Forecast (1986 Shape, 200-year)



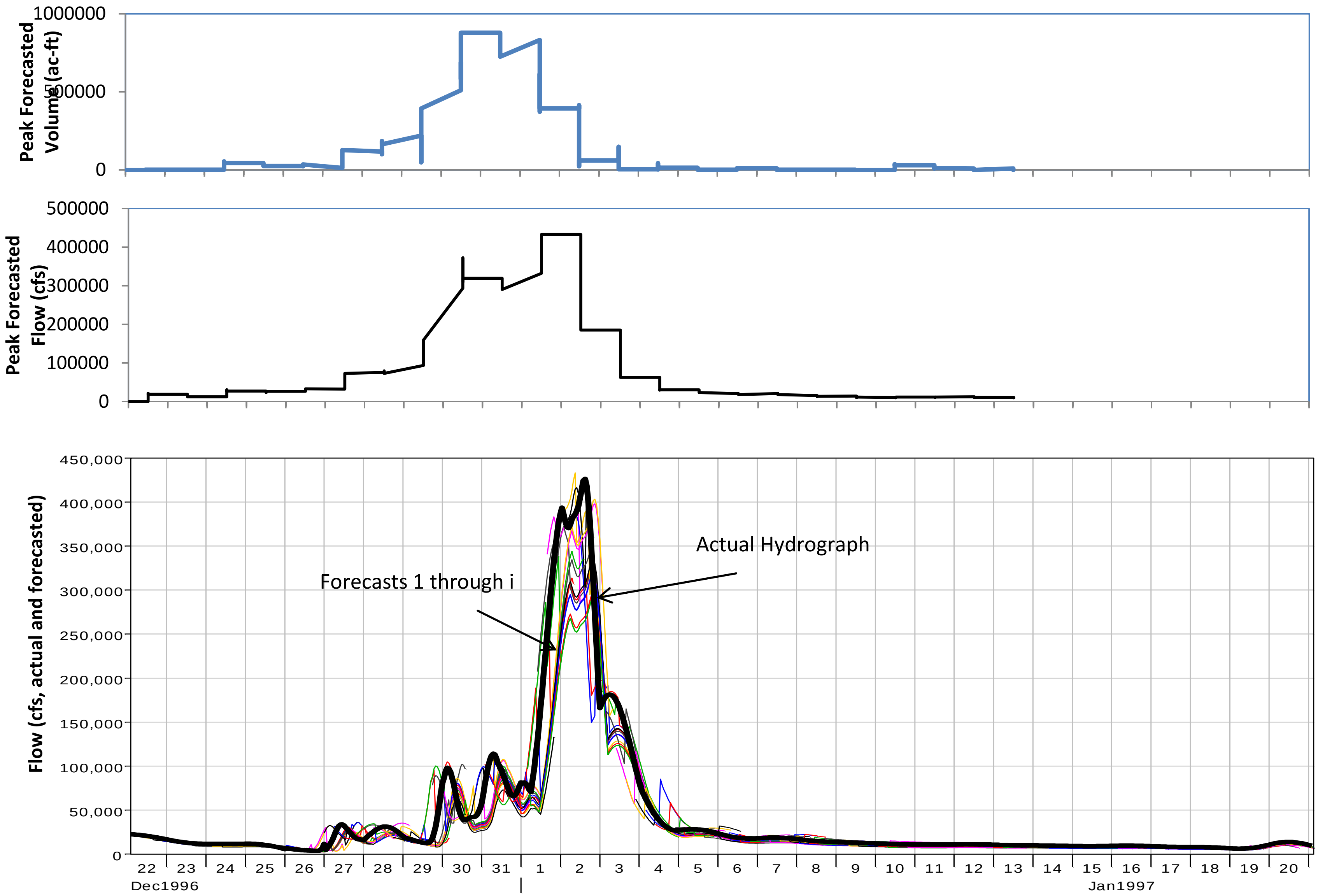
Late Forecast (1986 Shape, 200-year)



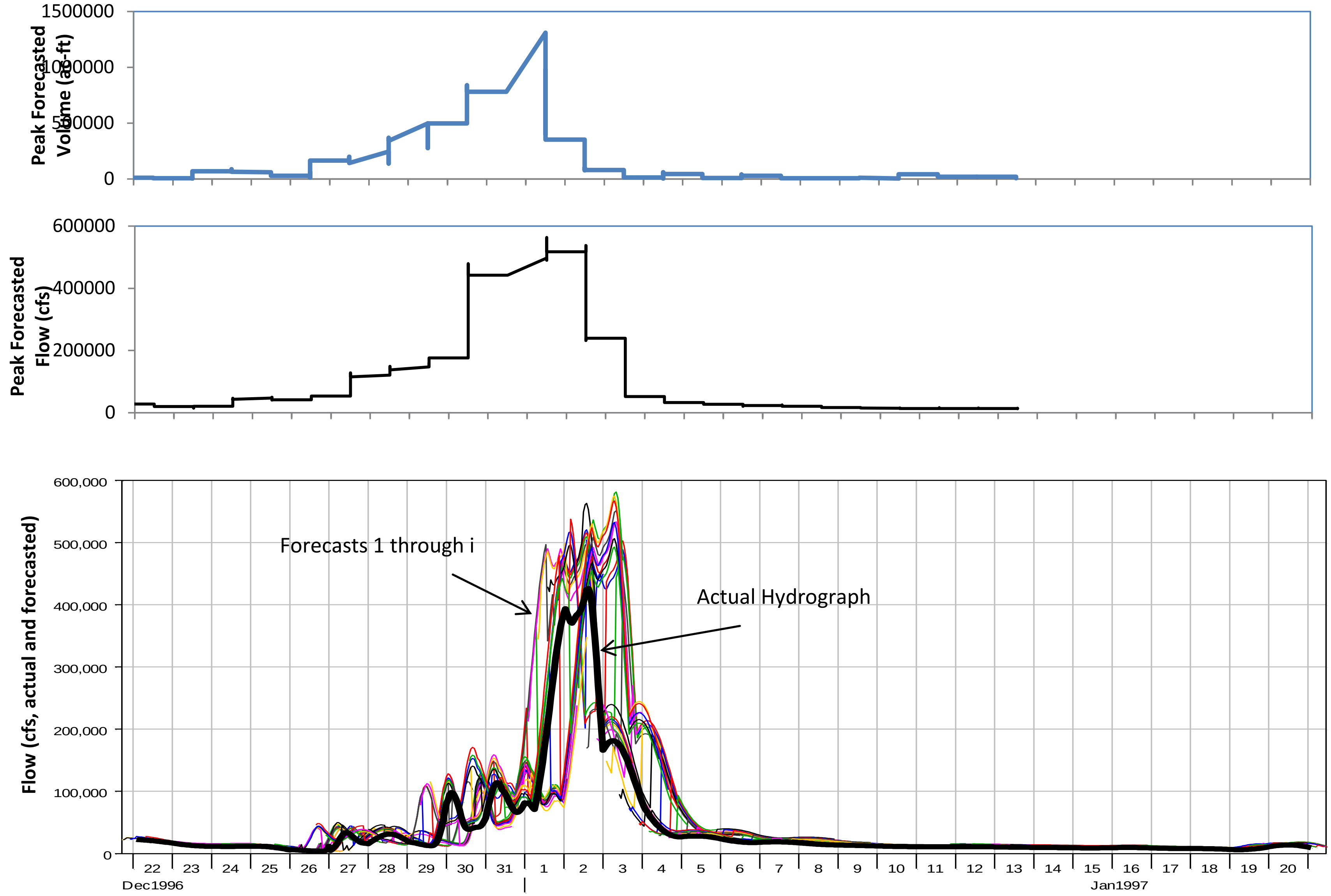
1997 Forecasts and 3-day summaries (actual hydrograph in bold)
On Time Forecast (1997 Shape, 200-year)



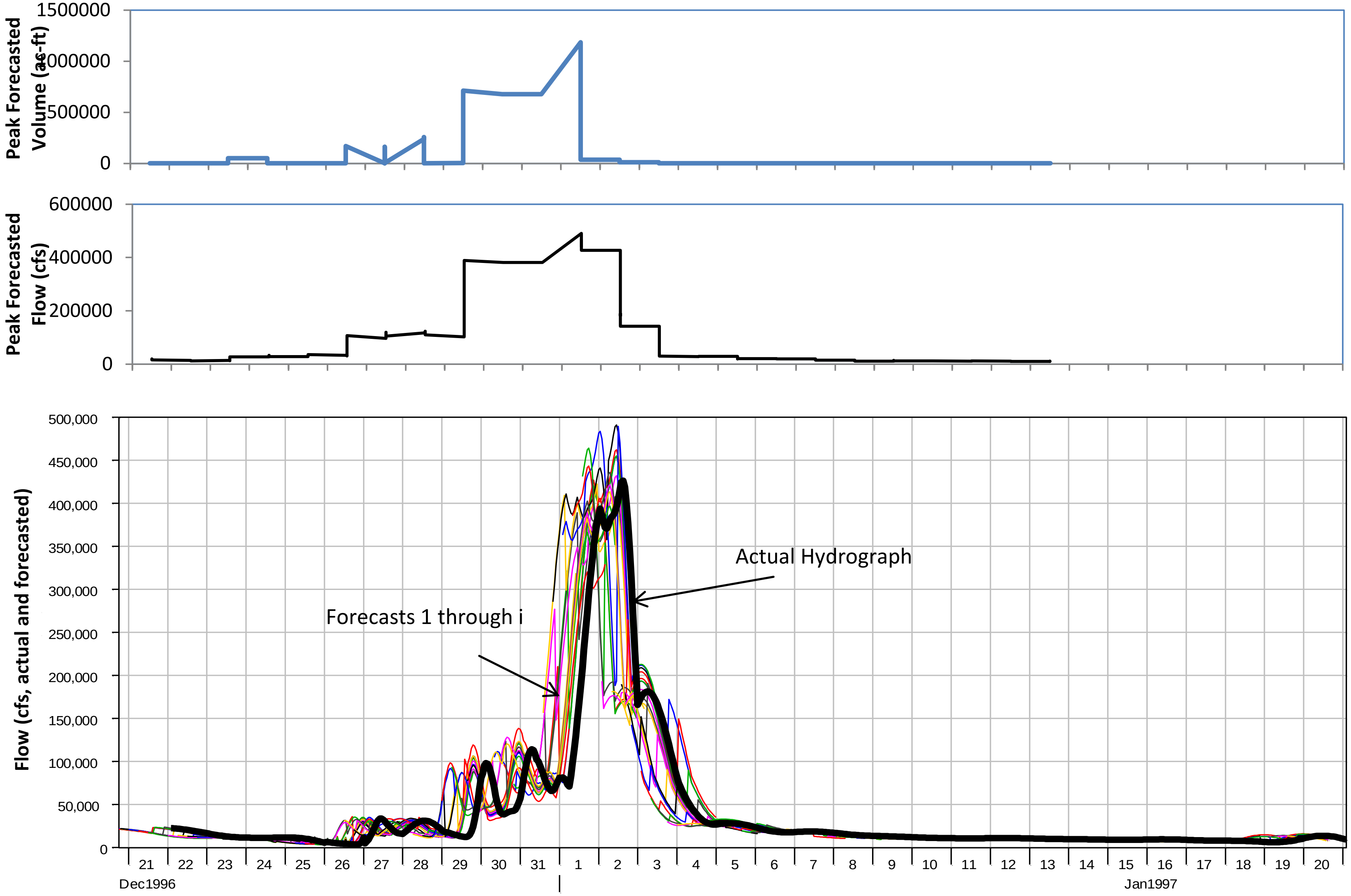
Low Forecast (1997 Shape, 200-year)



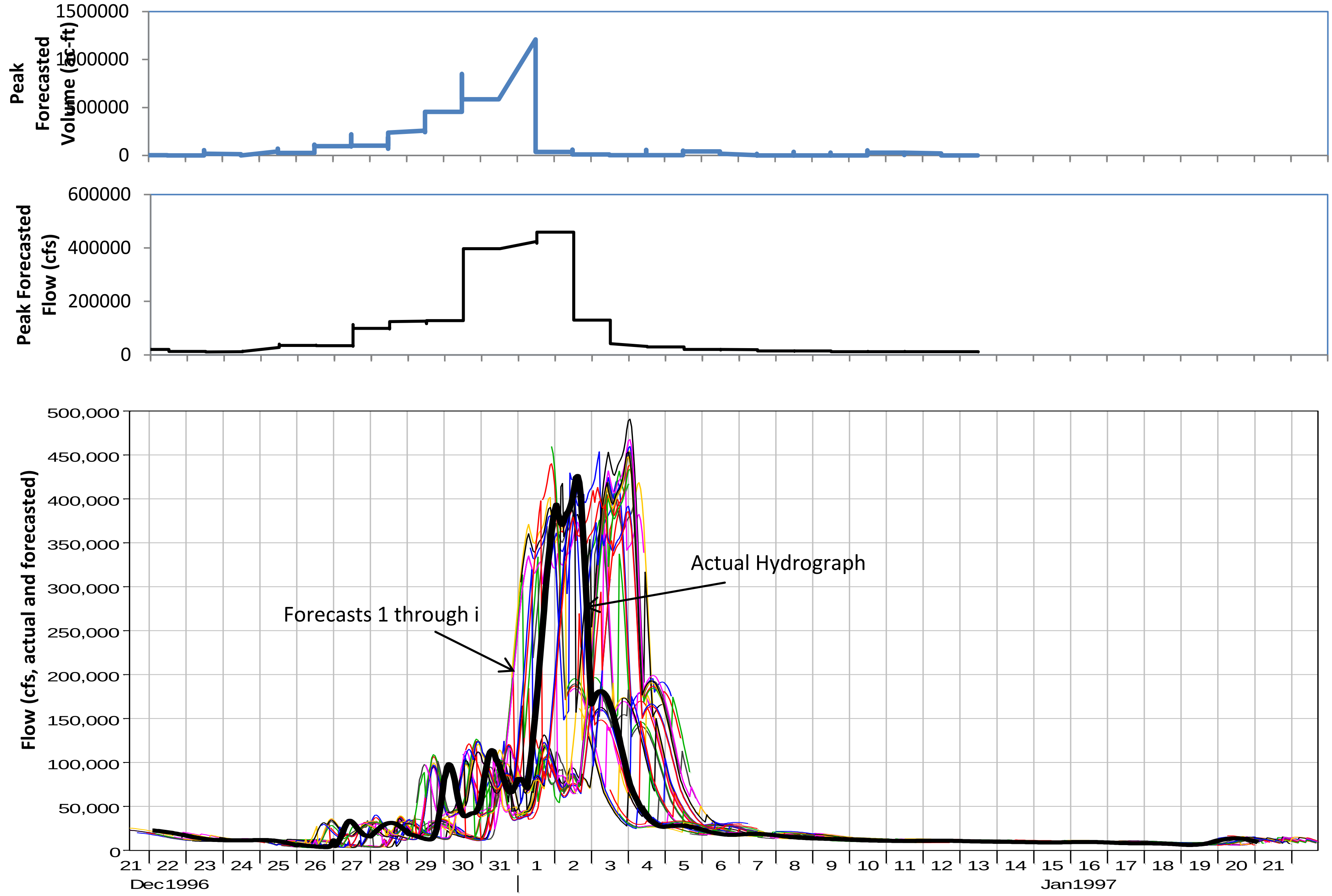
High Forecast (1997 Shape, 200-year)



Early Forecast (1997 Shape, 200-year)



Late Forecast (1997 Shape, 200-year)



Appendix C. Sample Calculation of Geotechnical Curve and Weighted Average of Failure Probability

Part 1. Calculation of Failure Probability for Each Event Shape and Initial Condition

	160000	**P(f) at flow threshold**	**Est. Time to Typical Failure (hr)**	**Adjusted P(f)**	
Hrs Outflow >=115 kcfs	59	0.03	720	.03*(59-54)/720 =	0.000
Hrs Outflow >= 130 kcfs	54	0.05	360	.05*(54-48)/360 =	0.001
Hrs Outflow >= 145 kcfs	48	0.09	180	.09*(48-44)/180 =	0.002
Hrs Outflow = 160 kcfs	44	0.14	72	.14*44/72 =	0.084
Hrs Outflow >160 kcfs	0				
Probability of Failure (Geotechnical)				Σ =	0.087
Probability of Failure (Overtopping)					0.000
Total Probability of Failure (PMF, 600 TAF)				=	**0.087**

	160000	**P(f) at flow threshold**	**Est. Time to Typical Failure (hr)**	**Adjusted P(f)**	
Hrs Outflow >=115 kcfs	53	0.03	720	.03*(53-45)/720 =	0.000
Hrs Outflow >= 130 kcfs	45	0.05	360	.05*(45-39)/360 =	0.001
Hrs Outflow >= 145 kcfs	39	0.09	180	.09*(39-35)/180 =	0.002
Hrs Outflow = 160 kcfs	35	0.14	72	.14*35/72 =	0.067
Hrs Outflow >160 kcfs	0				
Probability of Failure (Geotechnical)				Σ =	0.070
Probability of Failure (Overtopping)					0.000
Total Probability of Failure (SPF, 600 TAF)				=	**0.070**

	160000	**P(f) at flow threshold**	**Est. Time to Typical Failure (hr)**	**Adjusted P(f)**	
Hrs Outflow >=115 kcfs	58	0.03	720	.03*(58-48)/720 =	0.000
Hrs Outflow >= 130 kcfs	48	0.05	360	.05*(48-37)/360 =	0.001
Hrs Outflow >= 145 kcfs	37	0.09	180	.09*(37-33)/180 =	0.002
Hrs Outflow = 160 kcfs	33	0.14	72	.14*33/72 =	0.063
Hrs Outflow >160 kcfs	0				
Probability of Failure (Geotechnical)				Σ =	0.067
Probability of Failure (Overtopping)					0.000
Total Probability of Failure (1955, 600 TAF)				=	**0.067**

	160000	P(f) at flow threshold	Est. Time to Typical Failure (hr)	Adjusted P(f)	
Hrs Outflow >=115 kcfs	72	0.03	720	.03*(72-67)/720 =	0.000
Hrs Outflow >= 130 kcfs	67	0.05	360	.05*(67-60)/360 =	0.001
Hrs Outflow >= 145 kcfs	60	0.09	180	.09*(60-51)/180 =	0.005
Hrs Outflow = 160 kcfs	51	0.14	72	.14*51/72 =	0.097
Hrs Outflow >160 kcfs	0				
Probability of Failure (Geotechnical)				Σ =	0.103
Probability of Failure (Overtopping)					0.000
Total Probability of Failure		Total Probability of Failure (1964, 600 TAF)		=	**0.103**

	160000	P(f) at flow threshold	Est. Time to Typical Failure (hr)	Adjusted P(f)	
Hrs Outflow >=115 kcfs	143	0.03	720	.03*(143-39)/720 =	0.004
Hrs Outflow >= 130 kcfs	39	0.05	360	.05*(39-37)/360 =	0.000
Hrs Outflow >= 145 kcfs	37	0.09	180	.09*(37-20)/180 =	0.009
Hrs Outflow = 160 kcfs	20	0.14	72	.14*20/72 =	0.038
Hrs Outflow >160 kcfs	16				
Probability of Failure (Geotechnical)				Σ =	0.047
Probability of Failure (Overtopping)					1.000
Total Probability of Failure (1986, 600 TAF)				=	**1.000**

	160000	P(f) at flow threshold	Est. Time to Typical Failure (hr)	Adjusted P(f)	
Hrs Outflow >=115 kcfs	61	0.03	720	.03*(61-57)/720 =	0.000
Hrs Outflow >= 130 kcfs	57	0.05	360	.05*(57-51)/360 =	0.001
Hrs Outflow >= 145 kcfs	51	0.09	180	.09*(51-41)/180 =	0.005
Hrs Outflow = 160 kcfs	41	0.14	72	.14*41/72 =	0.078
Hrs Outflow >160 kcfs	0				
Probability of Failure (Geotechnical)				Σ =	0.084
Probability of Failure (Overtopping)					0.000
Total Probability of Failure (1997, 600 TAF)				=	**0.084**

	160000	P(f) at flow threshold	Est. Time to Typical Failure (hr)	Adjusted P(f)	
Hrs Outflow >=115 kcfs	66	0.03	720	.03*(66-63)/720 =	0.000
Hrs Outflow >= 130 kcfs	63	0.05	360	.05*(63-57)/360 =	0.001
Hrs Outflow >= 145 kcfs	57	0.09	180	.09*(57-52)/180 =	0.003
Hrs Outflow = 160 kcfs	52	0.14	72	.14*52/72 =	0.099
Hrs Outflow >160 kcfs	0				
Probability of Failure (Geotechnical)				Σ =	0.102
Probability of Failure (Overtopping)					0.000
Total Probability of Failure	Total Probability of Failure (1964, 400 TAF)			=	**0.102**

	160000	P(f) at flow threshold	Est. Time to Typical Failure (hr)	Adjusted P(f)	
Hrs Outflow >=115 kcfs	137	0.03	720	.03*(137-33)/720 =	0.004
Hrs Outflow >= 130 kcfs	33	0.05	360	.05*(33-29)/360 =	0.001
Hrs Outflow >= 145 kcfs	29	0.09	180	.09*(29-25)/180 =	0.002
Hrs Outflow = 160 kcfs	25	0.14	72	.14*25/72 =	0.048
Hrs Outflow >160 kcfs	21				
Probability of Failure (Geotechnical)				Σ =	0.050
Probability of Failure (Overtopping)					1.000
Total Probability of Failure (1986, 400 TAF)				=	**1.000**

	160000	P(f) at flow threshold	Est. Time to Typical Failure (hr)	Adjusted P(f)	
Hrs Outflow >=115 kcfs	62	0.03	720	.03*(62-59)/720 =	0.000
Hrs Outflow >= 130 kcfs	59	0.05	360	.05*(59-55)/360 =	0.001
Hrs Outflow >= 145 kcfs	55	0.09	180	.09*(55-49)/180 =	0.003
Hrs Outflow = 160 kcfs	49	0.14	72	.14*49/72 =	0.093
Hrs Outflow >160 kcfs	0				
Probability of Failure (Geotechnical)				Σ =	0.097
Probability of Failure (Overtopping)					0.000
Total Probability of Failure (1997, 400 TAF)				=	**0.097**

Part 2. Weighted Average of 12 Computed Probabilities of Failure.

Shape	Weighting Factor		
PMF	0.1	.1*(.087+.089)/2=	0.01
SPF	0.1	.1*(.07+1.)/2=	0.05
1955	0.1336	.13*(.067+.072)/2=	0.01
1964	0.1424	.14*(.103+.102)/2=	0.01
1986	0.2384	.24*(1.+1.)/2=	0.24
1997	0.2872	.29*(.084+.097)/2=	0.03
Weighted Avg P(f)		**Σ =**	**0.35**