Enhanced Freshwater Inflow to the Chesapeake Bay Through Reservoir System Operation: Extended Flood Peak Estimation

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Executive Summary

Real-time estimation of runoff hydrographs for watersheds under flood conditions is essential for efficient operation of flood control reservoirs. A technique for the real-time estimation of flood hydrographs generated from multiple basin runoff was examined on the North Branch of the Potomac River above Luke, Md. Deconvolution through a calibrated watershed model is used to estimate effective precipitation from observed hourly streamflow. The current estimate of effective precipitation provides a lower bound on runoff during the storm. When the response time for a watershed is long compared to the duration of precipitation, flood peaks may be anticipated with lead times comparable to the concentration time of the runoff producing watersheds.

The deconvolution of streamflow to precipitation over multiple watersheds, is extremely sensitive to model error. Effective precipitation could not be accurately estimated through the calibrated hydrologic model that was used. The sensitivity of precipitation estimates to model error indicates the need for adaptive forecasting, in which model error and forecast errors are simultaneously estimated in real-time.

The incorporation of meteorological data in precipitation estimation by deconvolution was demonstrated in real-time forecasting on the North Branch of the Potomac. The deconvolution of streamflow can provide a framework for uniting hydrometeorological data from diverse sources in real-time flood forecasting. The incorporation of National Weather Service Quantitative Precipitation Forecasts in hourly precipitation estimation is demonstrated.

Flood forecasting differs from the forecasting of many other time series in two fundamental ways. Flood forecasting is sequential and bounded in time by the duration of the storm. The value of a flood forecast methodology will depend more on the rate of change of the forecast residuals with each forecast, than on the mean and variance of the residuals. Flood forecasts predict the time series of runoff, not just a single flow. Procedures and metrics to evaluate a flood forecast must be based on performance over the entire flood event.

Three measures of forecast skill are described, and used to quantify the performance of the proposed methodology. The coefficient of efficiency, the coefficient of determination, and the coefficient of persistence are described, and used to quantify the performance of precipitation estimation in flood forecasting.

Extended Flood Peak Inference

1.1 Introduction

This report examines a technique for the real-time estimation of flood hydrographs generated from multiple basin runoff. Deconvolution through a calibrated watershed model is used to estimate effective precipitation from observed hourly streamflow. The current estimate of effective precipitation provides a lower bound on runoff during the storm. For extensive storm events flood peaks can be anticipated with lead times comparable to the concentration time of the runoff producing watersheds.

The flood peak estimation methodology can integrate the information available from a variety of different sensors in real-time flood forecasting. The incorporation of 24 hour Quantitative Precipitation Forecasts, available from the National Weather Service, in hourly precipitation estimation is demonstrated in the context of real-time flood forecasting.

Flood forecasts for reservoir operation should provide accurate estimates of peak discharge, time of peak, total runoff volume, and accuracy in predicting the entire hydrograph, in addition to accuracy in the prediction of flow for the next hour. The coefficient of efficiency, the coefficient of determination, and the coefficient of persistence are described, and used to quantify the performance of precipitation estimation in flood forecasting. The characteristics of these metrics emphasizes the special requirements of flood forecasting.

1.2 Extended Flood Peak Estimation

Real-time estimation of runoff hydrographs for watersheds under flood conditions is essential for efficient operation of flood control reservoirs. The runoff volume, peak discharge, and time of peak are all crucial variables guiding the timely commitment of available reservoir storage during floods. Simultaneous estimation of both timing and magnitude of runoff, from both controlled and uncontrolled watersheds will allow reservoir operations to best utilize existing storage to reduce flood damages downstream.

The use of observed streamflow and a calibrated hydrologic model to estimate effective precipitation can contribute to flood forecasting in two ways. Precipitation gages are not available on every watershed. For ungaged watersheds observed streamflow could provide a basis for flood forecasting. The optimal estimation of effective precipitation offers a framework to unite streamflow and raingage observations with radar imagery to provide a short-term, lower bound forecast of runoff. If a complete loss of hydrometeorologic data over a watershed were experienced, streamflow at the mouth of the watershed could still allow the estimation of the flood hydrograph with lead times comparable to the concentration time for the basin. Schwartz (1986) suggested the utility of estimating effective precipitation from streamflow with a simple example from a single basin. In this work the utility of estimating effective precipitation from observed streamflow is considered for a drainage area with multiple watersheds on the North Branch of the Potomac River.

Section 2 describes flood peak estimation for a basin with runoff contributed from multiple basins. A model of runoff and channel routing calibrated by the U.S. Army Corps of Engineers as part of the Bloomington Lake reformulation study, is used to represent the hydrologic characteristics of the North Branch of the Potomac River. Historical floods on the North Branch of the Potomac River at Kitzmiller are modeled and the routed contribution to the flood peak at Luke is developed. The estimates for a steep flood wave suggest the propagation of model error. The incorporation of meteorological data from both local weather instrumentation as well as National Weather Service forecast products in real-time precipitation estimation is demonstrated with an example using Quantitative Precipitation Forecasts.

Section 3 describes a number of metrics to quantify the performance of flood forecasts. Forecasts for three historical floods are examined in detail. The flood peak estimation methodology performs poorly, and is unable to provide reliable flow forecasts. Incorporating independent meteorological data dramatically improves forecast results. The poor performance of the deconvolution technique is shown to result from physically unrealistic parameters in the hydrologic model for the North Branch above Kitzmiller. The sensitivity of flood peak estimates to model error suggests the need for adaptive real-time forecasting.

In Section 4 the assumptions underlying storage routing are considered in detail. Under rapidly rising flow conditions the linear approximation used in storage routing may introduce significant numerical error. The channel routing calibration in the model of the North Branch above Luke is shown to produce physically implausible results.

2.1 Flood Peak Estimation

A calibrated hydrologic model is used to estimate the effective precipitation required to generate observed streamflow. The precipitation estimate is fully routed through the calibrated hydrologic model to generate the estimated runoff hydrograph.

No attempt is made to forecast short-term precipitation. The runoff hydrograph produced is therefore a lower bound on expected runoff. The natural time lag between rainfall and runoff may allow accurate estimation of effective precipitation from the initial rises in streamflow during a storm. This would in turn provide a useful lead time in preparing an accurate estimate of the runoff hydrograph. Use of the current estimate of observed precipitation to forecast the flood hydrograph, implicitly assumes no more precipitation will affect the basin. During an intense storm this may be the worst forecast to make. Routing the estimate of observed precipitation will provide a poor forecast early in the storm before most of the rain has fallen, and a good prediction late in the storm when rainfall has ended.

Estimated precipitation will be less than total storm depth, due to infiltration and bank losses. The estimated precipitation will underestimate total storm depth, making direct comparisons with precipitation gages inexact. Concentrating on effective precipitation, avoids the need to evaluate the added errors that would be introduced in estimating a loss rate or infiltration function. An alternative approach would estimate both precipitation and loss rate simultaneously.

The estimate of effective precipitation uses a deconvolution of streamflow through a hydrologic model of the routing and runoff processes. Deconvolution infers the inputs to a linear rainfall runoff model - precipitation - from observed streamflow. Using unit hydrographs to describe the transformation of effective precipitation to runoff, and linear routing in river channels, a calibrated basin model provides a set of constraints relating observed streamflow to precipitation. An optimization problem is formulated to determine the effective precipitation over each watershed that will generate runoff that best matches the observed streamflow.

In general we expect precipitation estimates to be poor early in the storm, and improve as streamflow is observed. Early in the storm, with few observations, many combinations of precipitation will appear to be consistent with the observed streamflow. While the best estimate of runoff will be made after the flood has receded, significant lags in runoff and routing may allow estimation of significant precipitation before the flood peak occurs. Observed streamflow is used to develop an optimal estimate of effective precipitation for the calibrated hydrologic model.

Errors in the representation of runoff and channel processes will be manifested as spurious estimates of precipitation. Model error may lead to precipitation estimates, consistent with the observed flow to date, that produce implausible volumes of streamflow when routed into the future. As the set of streamflow observations grows the feasible estimates of precipitation become more constrained and should become more accurate.

2.2 Flood Forecasting at Luke, Md.

The estimation of effective precipitation from multiple watersheds is performed for the drainage area above the USGS stream gage at Luke Md. A linearized hydrologic model of this drainage was calibrated by the U.S. Army Corps of Engineers (1980) and is used to describe the runoff characteristics of the basin. Luke receives runoff from four watersheds on the North Branch of the Potomac River, ranging in drainage area from 38 mi^2 to 103 mi^2. A schematic representation of the Corps' representation of the drainage above Luke is presented in Figure 1. With multiple basins the estimate of precipitation must partition runoff both temporally and spatially. Effective precipitation over each of the contributing watersheds will be simultaneously estimated. The estimated precipitation will reflect both the runoff characteristics of each of the basins, and the modification of runoff by channel routing.

Precipitation estimation requires continuous hourly streamflow observations. Hourly observations at Luke were not available for all of the floods considered. We therefore estimate the effective precipitation above Kitzmiller, and evaluate the forecast with respect to the observed hourly flows that are available at the Kitzmiller stream gage. The Kitzmiller flow is routed downstream to Luke. An area correction for the local runoff above Jennings Randolph Reservoir is combined with the routed Kitzmiller flow to provide an estimate of the natural, unregulated hydrograph below Jennings Randolph reservoir at Luke.

2.3 Estimation for Historical Floods

Continuous hourly observations of streamflow at the U.S. Geological Survey gage at Kitzmiller were obtained for the floods of October 1954, August 1955, and July 1978. The hourly runoff hydrographs are estimated for each of these events, covering a representative range of flow levels and runoff patterns.

The flood of August 1955 rose gradually over 12 hours to a peak discharge of 22000 cfs. Figure 2 shows both the flood hydrograph, and the forecasted hydrograph resulting from the precipitation estimated at hour 40. The combination of a gradual rise, and an **a posteriori** estimation of precipitation produces an excellent estimate of the flood hydrograph. A similar **a posteriori** estimate for the comparatively rapid rise of October 1954, (Figure 3), while offering a reasonably good fit, shows a persistent bias, underestimating the flood peak and overestimating the falling limb of the hydrograph. Despite the benefit of hindsight from estimating the effective precipitation at hour 30, Figure 3 indicates the propagation of persistent model error.

The presence of model error is of great concern in this estimation procedure. The degrees of freedom provided by considering multiple basins as well as channel routing, combined with a consistent bias in the hydrologic model, can lead to a precipitation estimate and a resulting flood forecast that is dominated by model error rather than streamflow observations. The value of estimating precipitation from observed streamflow lies in the information provided by the calibrated hydrologic model. If the model is biased, the estimated precipitation will be biased, limiting the value of the proposed methodology.

Errors in estimated precipitation can only be identified from differences between predicted and observed streamflow. This suggests the value of additional, independent hydrometeorological data in forecasting.

2.4 Incorporating Independent Meteorological Data

In this section Quantitative Precipitation Forecasts (QPF's) prepared by the National Weather Service are incorporated in the precipitation estimation methodology. For purposes of estimating an hourly flood hydrograph a QPF provides relatively coarse resolution of the spatial and temporal distribution of rainfall. The QPF represents an experienced forecaster's interpretation of the output of a large scale atmospheric circulation model and current observations from precipitation gages. The QPF gives a regional estimate of likely precipitation depths for the next 24 and 48 hours over the continental United States.

The QPF for July 3 1978 is shown in Figure 4. The July 3rd QPF suggests a 24 hour precipitation total of 2 inches is possible over the North Branch of the Potomac River, with an additional inch of rain possible during the following 24 hours (Figure 5). The QPF is updated after 12 hours. The update shown in Figure 6 indicates the 24 hour storm total for the North Branch may be as high as 3 inches.

On July 4 a new QPF is produced, as shown in Figures 7 and 8. The 24 hour isohyetals, combined with the updated QPF from July 3 suggest the 48 hour storm total for the North Branch could reach 5 inches. The July 4 update, shown in Figure 9 shows that the storm system moved to the southeast, and was no longer centered over the North Branch.

Effective precipitation is estimated with a storm depth constraint derived from the QPF's. The July 3 QPF yields an upper bound constraint on the storm depth for the first 12 hours of 2 inches. After 12 hours the updated QPF is translated into an upper bound constraint on the total estimated precipitation for the first 24 hours of 3 inches. Using the July 4 QPF's the estimated storm total for 48 hours is bounded at 5 inches. The results of incorporating meteorological data in the form of simple constraints on total precipitation are discussed in detail in section 3. This use of QPF's indicates one way in which independent meteorologic data can be incorporated in the methodology used to estimate precipitation for flood forecasting.

3.1 Forecast Performance

In this section three metrics for evaluating specific performance characteristics of a forecast methodology are described. The coefficient of efficiency offers an overall measure of the variation in streamflow explained by the forecast. The coefficient of determination is a measure of the relative explanatory power of the forecast, when systematic forecast errors are accounted for. A simple "persistence" forecast predicts streamflow in the next hour will be the same as the current observed flow. The coefficient of persistence quantifies the relative explanatory power of the forecast methodology, compared to the persistence forecast.

The time series of forecast metrics reflect the special characteristics of flood forecasting. The metrics are used to evaluate sequential hourly forecasts for the historical floods of October 1954, August 1955 and July 1978. The metrics are used to quantify the value of incorporating QPF information using forecasts for the flood of July 1978.

3.2 Forecast Metrics

Kitanidis and Bras (1980) described several metrics of forecast performance, and applied them to a real-time flood forecasting problem. Three of these metrics are described and modified to evaluate sequential flood forecasts. The metrics describe the relative variation explained by the forecast methodology, compared to a simple alternative forecast.

Coefficient of Efficiency C_e

The Coefficient of Efficiency, C_e, is a measure of the relative skill of the forecast methodology compared to a mean value forecast. If $Q(t)$ and $Q_f(t)$ denote the observed and forecasted streamflow at time t respectively, the sum of squared forecast residuals can be calculated as :

$$SS_f = \sum_{i=1}^{T} (Q(i) - Q_f(i))^2$$

where T is the length of the forecast horizon. Similarly the squared residuals from a mean value predictor are denoted as:

$$\overline{SS} = \sum_{i=1}^{T} (Q(i) - \bar{Q})^2$$

where $\bar{Q}$ is the mean flow for the period. The coefficient of efficiency is calculated as:

$$C_e = 1 - SS_f / \overline{SS} .$$

C_e is a measure of the variation about the mean explained by the forecast. When the forecast is exact for all flows, C_e will equal 1. If the forecast provided no additional skill compared to the mean value of streamflow, C_e will equal zero. C_e can also take on negative values if the forecast errors are more variable than the variation about the mean. This will be the case for early forecasts in which little effective precipitation has been observed.

Coefficient of Determination C_d

The coefficient of determination is similar to the coefficient of efficiency, but takes into consideration systematic errors in the forecast. Instead of calculating the forecast residual using the forecasted flow, an estimated flow is first calculated from the regression of observed flow and forecasted flow. In this way any linear, systematic error in the forecast methodology is corrected. The squared residuals are calculated as:

$$SS_e = \sum_{i=1}^{T} (Q(i) - Q_e(i))^2$$

where

$$Q_e(i) = a + b * Q_f(i)$$

based on the prior linear regression of $Q(t)$ on $Q_f(t)$. The coefficient of determination is calculated as :

$$C_d = 1 - SS_e / \overline{SS} .$$

C_d, like C_e will equal 1 for a perfect forecast, and decrease to 0 for a forecast explaining no more variation than the mean. The use of a corrected forecast, Q_e means C_e will always be bounded from above by C_d. The difference between C_e and C_d is a relative measure of the systematic bias in the forecast methodology.

Coefficient of Persistence C_p

The coefficient of persistence is a measure of the relative one-step-ahead performance of the forecast methodology compared to the persistence forecast. The variation explained by the persistence forecast of no change, is calculated as:

$$SS_p = \sum_{i=1}^{T} ((Q(i) - Q(i-1))^2$$

The coefficient of persistence is then defined as

$$1 - SS_f / SS_p .$$

3.3 Application to Flood Forecasting

The coefficients, C_e, C_d, and C_p, along with the relative measure of bias, C_d-C_e, allow the accuracy of the forecast methodology to be quantified and compared to meaningful stationary alternatives (such as the mean). These metrics can be viewed as relative measures of correlation between the observed flow values, and the forecast.

Flood forecasting differs from the forecasting of many other time series (such as daily water demand, or monthly flow volumes) in two fundamental ways. First, flood forecasting is sequential and bounded in time by the duration of the storm event. In most static time series applications, a forecast methodology is used to generate a single estimate of a forecasted quantity. The forecast is then compared to the observed value, and a time series of residuals is generated. Traditional measures of forecast performance focus on the statistical properties of this residual time series. The recursive nature of flood forecasting means there are now repeated, sequential estimates of forecast quantities. Sequential forecasts now lead to a time series of sequential estimates for each observation, and a time series of forecast residuals. Consistent, unbiased, minimum variance estimates are as desirable in flood forecasting as they are in any other forecasting procedure. The value of a flood forecasting methodology will depend more on the rate of change of the forecast residuals with each forecast, than on the mean and variance of the residuals.

The second distinguishing feature of flood forecasting, is the nature of the forecast itself. Flood forecasts predict the time series of runoff, not just a single flow. Procedures and metrics to evaluate a flood forecast must be based on performance over the entire flood event, taking into account the increased uncertainty of the predictions of later flow.

The performance metrics are intended to quantify the statistical accuracy of the forecast methodology. All residuals for all forecasts could be used to calculate the values of the performance metrics. This essentially treats the residuals from each forecast as i.i.d. random variables, and uses the performance metrics to characterize a forecast methodology by the descriptive statistics of the (assumed stationary) residuals it generates.

To account for the sequential character of the flood forecasting, the performance metrics are calculated for each hourly forecast. This creates a time series of performance metrics. The performance of the forecast methodology is judged by the time series of performance metrics over the duration of the storm. We expect forecasts to be poor early in the storm and gradually improve through time. Good forecasts will converge to metric values close to 1. The most desirable forecast will show this improvement in the forecast metric early in the storm, prior to the flood peak. The evaluation of a forecast methodology using a time series of descriptive metrics, each based on a time series of forecast residuals, provides a better measure of sequential forecast performance than the calculation of a single forecast metric.

3.4 Application to Historical Floods

Sequential observations of hourly streamflow were used to develop sequential estimates of hourly effective precipitation totals for three historical floods. The estimated precipitation was routed through the calibrated hydrologic model of the North Branch above Luke in Figure 1, to produce a lower bound forecast of runoff for the storm. Early in the storm, before significant precipitation has fallen, the routed precipitation will produce inconsequential runoff. While this is a lower bound for the flood hydrograph, it provides no guidance about the flood. The residual error of this lower bound will be extremely large compared to both the mean of the observed flow, as well as the persistence forecaster. The performance metrics will reflect this poor forecast skill, taking on large negative values.

The performance metrics should show a significant improvement in estimating runoff as we observe more streamflow during the storm. Each historical storm is analyzed below. The forecast metrics are used to compare the value of QPF information in the estimation-forecasting methodology for the flood of July 1978. In every case the difference between C_e and C_d was less then 1% indicating no systematic forecast bias. The forecasts are analyzed using C_d, C_p, and the change in root mean square error during the storm.

Figures 2 and 10 show the observed and **a posteriori** forecast for the floods of August 1955 and July 1978 respectively. The extremely close fit of the observed hydrograph and the **a posteriori** forecast is not unexpected. The **a posteriori** forecast is generated from precipitation estimated after the storm is over. Using the complete flood hydrograph gives the best possible precipitation estimate for the storm. The hydrograph generated from the **a posteriori** estimate of precipitation is the best forecast that could have been produced. Any errors in the predicted hydrograph reflect errors in the hydrologic model of the basin. The flood of October 1954 (Figure 3) indicates significant model error.

Sequential flood forecasts were prepared for the flood of August 1955 with poor results. Figure 11 shows the root mean squared error (rms) for each flood forecast through hour 30. Contrary to expectation, the rms error increases on the rising limb of the hydrograph, and does not improve as more observations of streamflow become available. The flood hydrographs predicted at hours 14, 15, and 16, along with the observed flood hydrograph, are shown in Figure 12. The underestimation of streamflow at hour 14, 7 hours before the flood peak is not surprising. A significant amount of the precipitation generating the flood peak has not yet fallen, and the forecast makes no attempt to predict future precipitation. The peak forecast from hour 15 is two hours early, and within 3,000 cfs of the true flood peak, but the rising limb of the hour 15 forecast shows significant error. The hour 16 forecast shows dramatic errors, calling for a 50,000 cfs flood peak, while significantly underestimating the observed rising limb.

In contrast to the **a posteriori** estimate of Figure 2, the forecasts produced during the August 1955 flood are unable to estimate effective precipitation from observed streamflow. Figures 11 and 12 indicate that the hydrologic model in Figure 1 is not able to fit observed streamflow without extreme, unrealistic estimates of precipitation. The model error suggested in Figure 3 is dominating the results for the 1955 flood.

Forecasts for the July 1978 flood (Figure 10) are prepared using constraints on precipitation derived from the QPF information described in section 2.4. Despite uncertainty early in the storm, Figure 13 shows that the rms error decreases through the storm, as expected. The value of using QPF information in hourly flood forecasting is suggested by the difference in rms error for forecasts prepared with, and without QPF derived constraints, shown in Figure 14. The dramatic improvement in the forecasts that use QPF information is evidenced in the predicted hydrographs shown in Figure 15. The underestimation of runoff at hour 11, early in the storm is expected. At hour 12, 6 hours before the crest of the flood, the estimate of maximum discharge differs from the true peak discharge by only 2,000 cfs. At hour 13 the flood peak is overestimated by about 3,000 cfs. These forecasts are based only on observed streamflow, using no data from precipitation gages. Their accuracy for a 5 hour lead time is surprisingly good.

Good forecast performance using QPF information is demonstrated in Figure 16. The coefficient of efficiency shows significant explanatory power for the QPF-based forecasts in almost every hour. Forecasts that do not use QPF information are extremely poor, as shown in Figure 17. The improvement in hourly forecasting from considering 24 hour QPF information is dramatic. The explanation for this remarkable improvement is suggested by comparing the coefficient of persistence for the two sets of forecasts.

The coefficient of persistence is a measure of one-step-ahead forecast accuracy. Although Figure 18 shows a significant improvement resulting from the use of QPF information, the QPF based forecast shows a progressive degradation in one-step forecast skill on the falling limb of the hydrograph. The one hour forecast late in the storm should be most accurate, since there is no uncertainty about future precipitation. Surprisingly, Figure 18 shows the one step ahead predictions of stream flow are four to five times more variable than a prediction of no change in flow. The explanation of these erratic results is found in Figure 19. The forecast at hour 23 slightly overestimates the falling limb of the hydrograph. A physically unrealistic approximation in channel routing, discussed in detail in section 4, makes it possible to lower the estimated hydrograph at hour 23 by **increasing** the precipitation estimated at hour 23. This large increment in precipitation at hour 23 is forecasted to produce the large increase in streamflow shown in Figure 19. The model error that was suggested by the relatively poor estimate of the October 1954 flood shown in Figure 3, is identified as physically unrealistic channel routing. Section 4 describes the cause of this routing error.

In this case model error led to extreme overestimation of effective precipitation. The use of QPF derived information fortuitously limits the propagation of this model error, producing the dramatic improvement in the forecasts described in Figures 13-17. The effect of fundamental model error dominates effective precipitation estimation, causing the method to fail using the hydrologic model in Figure 1.

Despite error propagation from the channel routing model employed, the analysis suggests how significant improvements can be realized by including multiple forms of hydrometeorological data in the estimation of runoff producing rainfall. The deconvolution procedure developed is extremely sensitive to model error. Further efforts in merging multiple sensor data to improve flood forecasting should concentrate on adaptive procedures (Kitanidis and Bras 1980a,b, Wasimi and Kitanidis 1980, Georgakakos and Bras 1982) that explicitly estimate both model inputs and model errors in real-time.

4.1 Flood Routing

The channel routing component of the hydrologic model used for precipitation estimation is re-examined in detail. Linearization of channel routing is discussed in comparison to the full dynamic wave equation. The accuracy of the linear approximation of the equation of flow in an open channel is examined and shown to be unacceptable for rapid changes in flow.

Muskingum routing was used to represent channel processes in the hydrologic model of Figure 1. This follows the approach used by the Baltimore District of the U.S. Army Corps of Engineers (1980) for the North Branch of the Potomac River. The parameters for the muskingum channels used to route runoff from Steyer and Mt. Storm were taken from the Corps' Bloomington Reformulation Study (1980).

Muskingum routing is discussed in the context of the hydraulics of open channel flow. Muskingum routing, uses a linear approximation of the dynamic force balance in a channel leading to a description of flow that is dominated by channel storage. For this reason muskingum routing is referred to as a storage routing technique.

We briefly examine the equations of open channel flow to identify the assumptions underlying this linear approximation. For a rapidly rising flood wave the assumptions implicit in the muskingum approximation may be invalid. For flood routing on the North Branch, we re-examine the calibrated parameter values for channel routing and conclude that a significant numerical error is introduced by the linear routing assumption. This error is propagated through the flood inference methodology and can only be corrected by using a more complete description of the equations of flow.

4.2 Friction Slope

Consider the Chezy Equation

$$v = C\sqrt{R\ S} \tag{4.1}$$

which relates velocity v, to friction slope S. R is the hydraulic radius defined as the cross sectional area of flow divided by the wetted perimeter, and C is the "Chezy Coefficient". The discharge through a section of area A is therefore

$$Q = C\ A\sqrt{R\ S} \tag{4.2}$$

From the conservation of momentum the friction slope, or the slope of the energy surface (dH/dx), is given as

$$Sf = So + \frac{dy}{dx} + \frac{dv}{g\ dt} + \frac{v\ dv}{g\ dx} \tag{4.3}$$

where the bed slope So, represents the force of gravity, dy/dx is a pressure force related to changes in depth, and the last two terms are measures of local and convective acceleration (Doyle et al. 1983).

For a gradual change of discharge in a steep channel the gravity force, So dominates the other terms. Sf = So and (4.2) can be written

$$q = d\ C\sqrt{R\ So} \tag{4.4}$$

where q is the discharge per unit width of channel and d is the depth in a channel of uniform cross section. In this form outflow from a channel is a linear function of depth (reflecting the volume of water in channel storage).

Muskingum routing uses this approximation to treat channel storage as a linear reservoir in which channel storage V, is a linear function of outflow:

$$V = K\ O \tag{4.5}$$

In muskingum routing an increased inflow to the channel I, contributes a volume (I-O) to wedge storage (Henderson 1966). Not all of this wedge storage contributes to outflow in the current time period. Muskingum routing treats channel storage as the sum of outflows from two linear reservoirs:

$$V = K\ [\ O + x\ (I-O)\ ] \tag{4.6}$$

where x is the proportion of incremental inflow contributing to wedge storage. Equation (4.6) is the basic description of muskingum routing. Standard treatments (Viessman et al. 1977) show how the finite difference solution of the continuity equation for a channel with eq. (4.6) leads to the muskingum routing equation :

$$O_t = C0\ I_t + C1\ I_{t-1} + C2\ O_{t-1} \qquad (4.7)$$

where the coefficients C0, C1, and C2 are expressions in K and x. The basis for this routing is the assumption in equation (4.4), that the friction slope is dominated by the bed slope. In a frequently cited example of this so called kinematic wave assumption, Henderson (1966) considers numerical values for each of the terms in eq. (4.3) for a flood wave in an alluvial valley rising from 10,000 cfs to 150,000 cfs and then falling to 10,000 cfs in 24 hours. The following values were estimated for each of the terms of the friction slope:

	So	dy/dx	vdv/gdx	dv/gdt
ft/mile	26	1/2	1/8-1/4	1/20

For this example the kinematic wave is a good assumption. We note that much less severe slopes are common. For gentle slopes and a rapid rise in stage, the pressure term dy/dx could become significant. Shoemaker and Miller (1985) surveyed the slope of the Potomac River between Point of Rocks and Seneca Pool as .88 ft/mile. Mays and Unver (1987) found it necessary to use the full dynamic wave equation to accurately route flood waves through complex channels on the Lower Colorado River.

In a rapidly rising flood the pressure force of the sloped water surface will be interpreted as a significant volume of channel storage. For flood waves in which the kinematic wave approximation is not valid, muskingum routing will introduce significant errors in flow routing. This leads to large errors in the back routing of observed streamflow to estimated precipitation.

To demonstrate the effect of these errors we consider the muskingum channel calibration used to route flow to Kitzmiller, Md. The parameter values for these channels selected by the Corps of Engineers (USA COE 1980) were K=2.5, x=.4. Inflow to this channel is routed as

$$O_t = -0.25\ I_t + 0.75\ I_{t-1} + 0.50\ O_{t-1} \qquad (4.7)$$

The negative value of C0 can actually decrease channel outflow for a steeply rising inflow. In the extreme case of a very large increase from baseflow (as occurs early in the flood of August 1955) this calibration of the muskingum channel could produce negative values of streamflow.

Muskingum routing (and, in particular the calibrated parameter values used for the channels above Kitzmiller,) is not appropriate for routing a steeply rising flood wave. The numerical error introduced through this linear approximation propagates through the precipitation estimation procedure producing unrealistic values of precipitation. The error introduced in a rapidly rising flood wave suggests the kinematic wave approximation is invalid.

This is reinforced by Figures 2 and 4. Both figures show the best, **a posteriori** estimate of the flood hydrograph. Each hydrograph was generated by first estimating effective precipitation at the end of the storm, using all available flows, and then routing that inferred precipitation through the same rainfall runoff model used for estimation. The estimated hydrographs represent the best estimate that could have been obtained, and any errors are due to model error. The flood hydrograph for August 1955 had a relatively gradual rise, building to flood crest over 12 hours. For this gradual rise the fit of the estimated hydrograph is quite close. The October 1954 flood showed a much steeper rise and as indicated in Figure 4, significant errors in the best estimate of the hydrograph. The consistent under estimation of the peak discharge and overestimation on the falling limb suggests a persistent error that becomes significant in the more rapid rise seen in the October 1954 flood.

Despite the attractive computational aspects of using a linear channel approximation, historical floods on the North Branch of the Potomac River suggest a more accurate hydraulic representation of channel routing is warranted. In some streamflow routing applications an error of 2000 cfs may be acceptable when the flood peak is nearly 35,000 cfs. For the precipitation estimation procedure considered here, accurate inference of effective precipitation over a drainage area with multiple watersheds and multiple channels is extremely sensitive to model error. The procedure attributes all errors to unobserved precipitation inputs. Persistent numerical errors in the rainfall runoff model will make consistent accurate precipitation estimation impossible.

Conclusion

A flood forecasting methodology was tested on the North Branch of the Potomac River above Luke, Md. The estimation of effective precipitation in real-time was attempted through the deconvolution of observed streamflow through a calibrated hydrologic model. Effective precipitation could not be accurately estimated through the calibrated hydrologic model that was used. The sensitivity of precipitation estimates to model error indicates the need for adaptive forecasting.

Accurate channel routing during flood conditions may require a more complete hydraulic model of open channel flow than is commonly used. For gradually varied flow in relatively steep channels, accurate routing of streamflow can be achieved with linear storage routing. Rapid rises in flow observed in flashy floods can make the approximation error in linear storage routing significant.

Flood forecasting is sequential and bounded in time by the duration of the storm event. The value of a flood forecasting methodology is judged by the rate at which the accuracy of sequential forecasts improves as additional information is received during the flood. The accuracy of a flood forecast is judged over the entire forecasted hydrograph, including the accuracy in predicting the peak discharge, the time of peak discharge, and the total volume of runoff over the forecast horizon. Three metrics were used to quantify the performance of the forecast methodology. The forecast method is evaluated using the time series of performance metrics for the duration of the flood.

The incorporation of meteorological data in precipitation estimation by deconvolution was demonstrated in real-time forecasting. The examples from the North Branch of the Potomac indicate how the flood forecasting method can provide a framework for uniting hydrometeorological data from diverse sources in flood forecasting. Despite the presence of significant model error described above, the incorporation of meteorologic data and streamflow observations with a hydrologic model can improve the forecasting of flood hydrographs in real-time.

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Figure 1

1. North Branch Potomac at Steyer, Md.

2. Stony River, Md. near Mt. Storm

3. Local Area above Kitzmiller, Md.

4. Local Area above Bloomington Lake

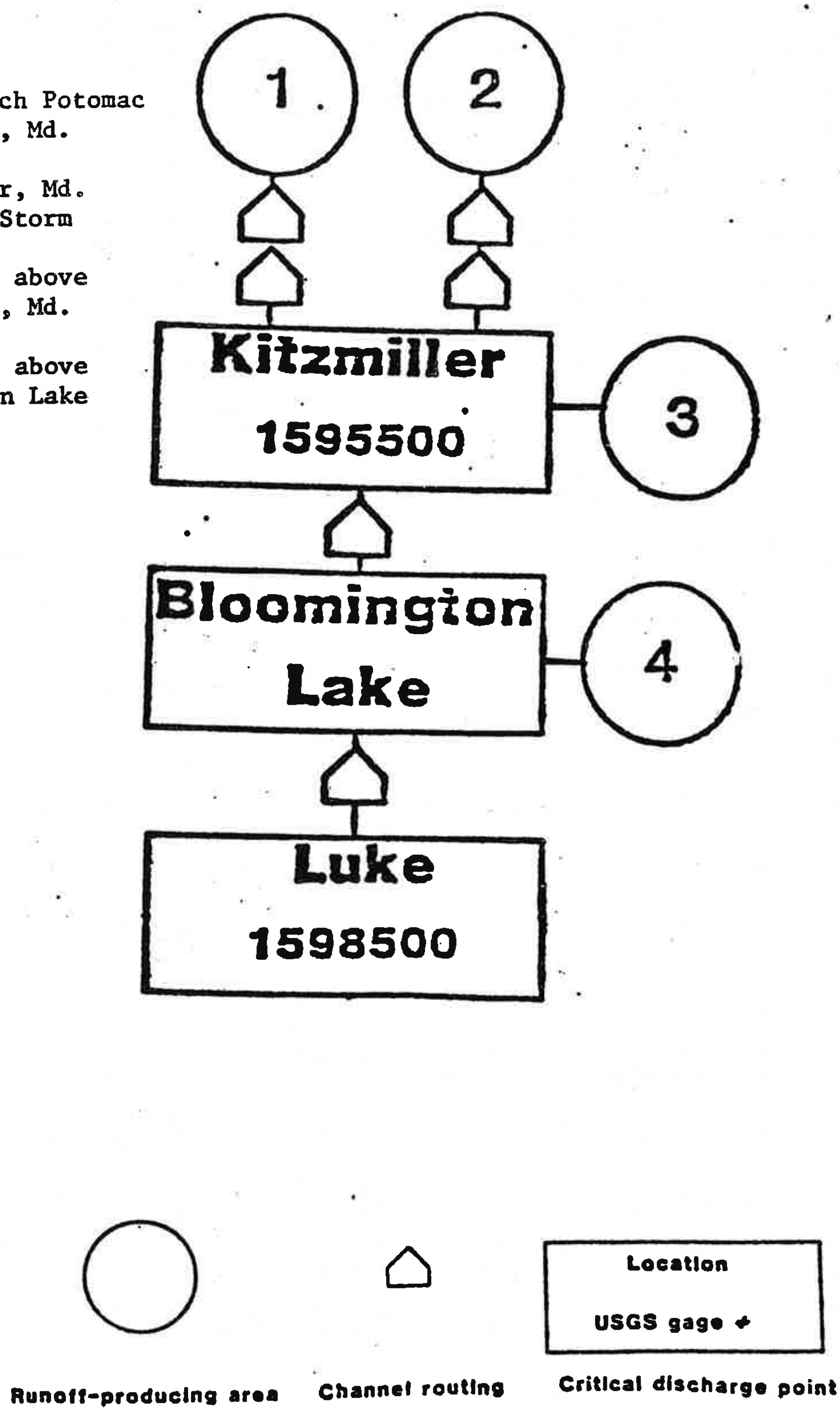


Figure 2

FLOOD ESTIMATION AT KITZMILLER

AUG '55

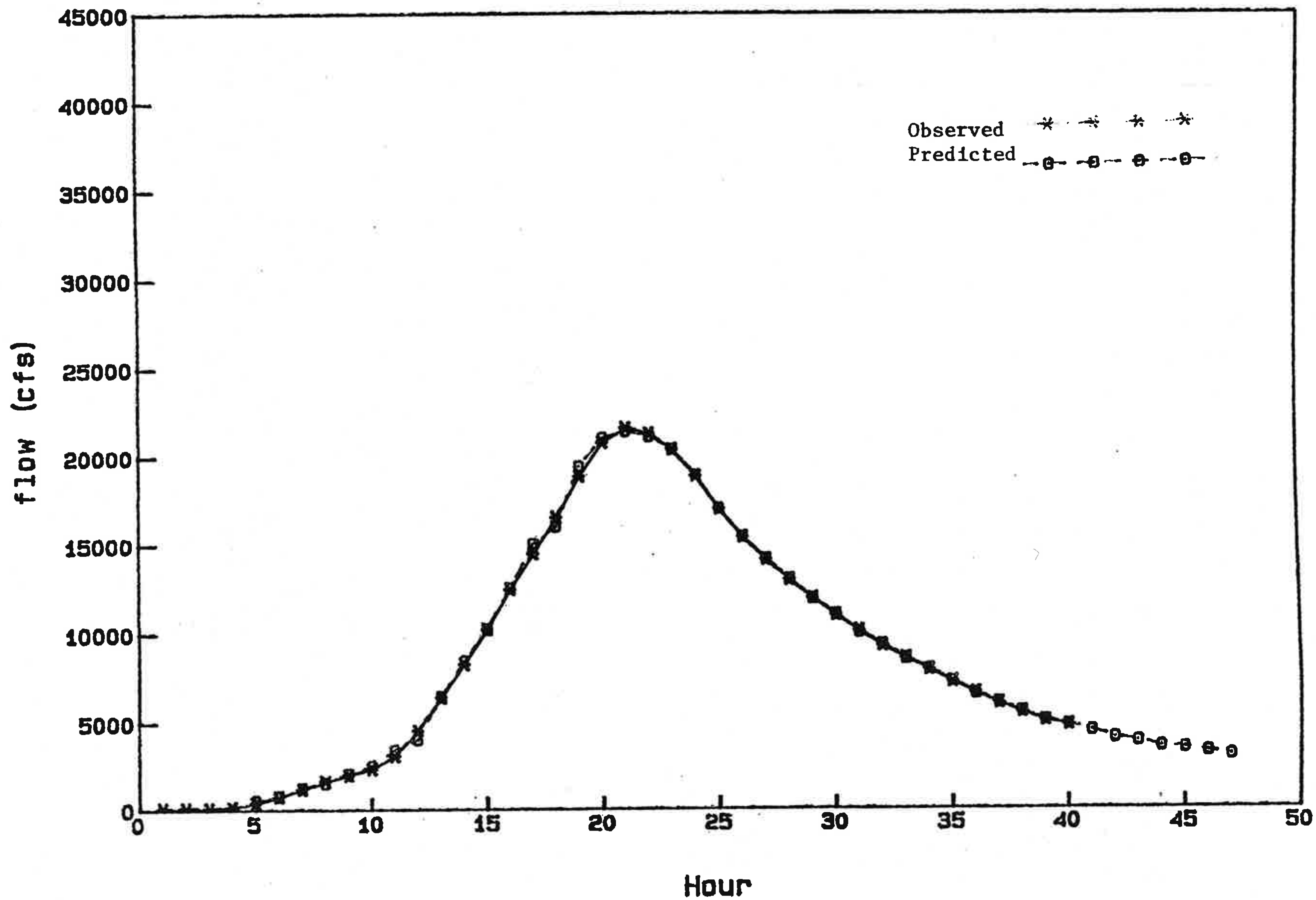


Figure 3

FLOOD ESTIMATION AT KITZMILLER

OCT '54

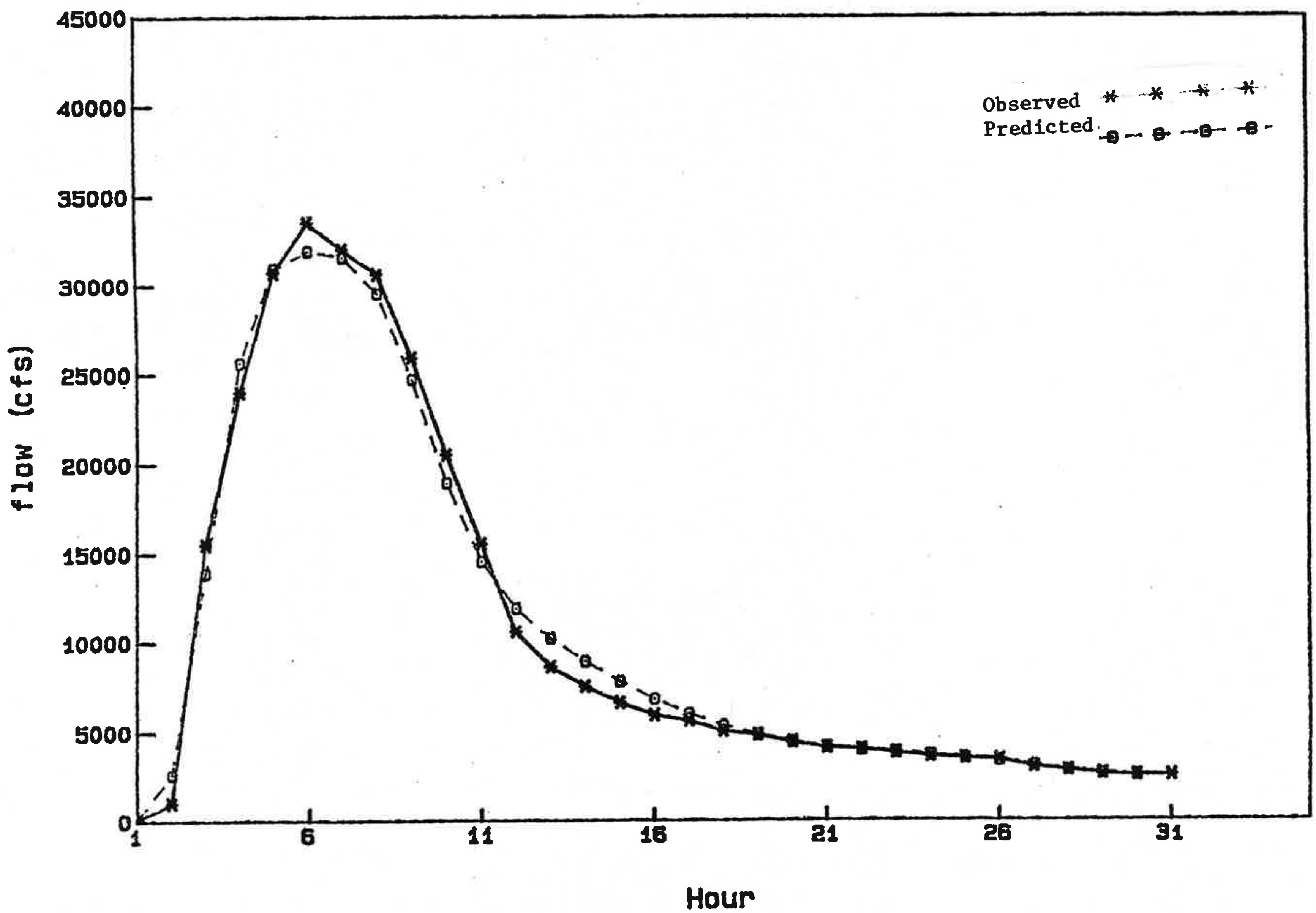


Figure 4

Figure 5

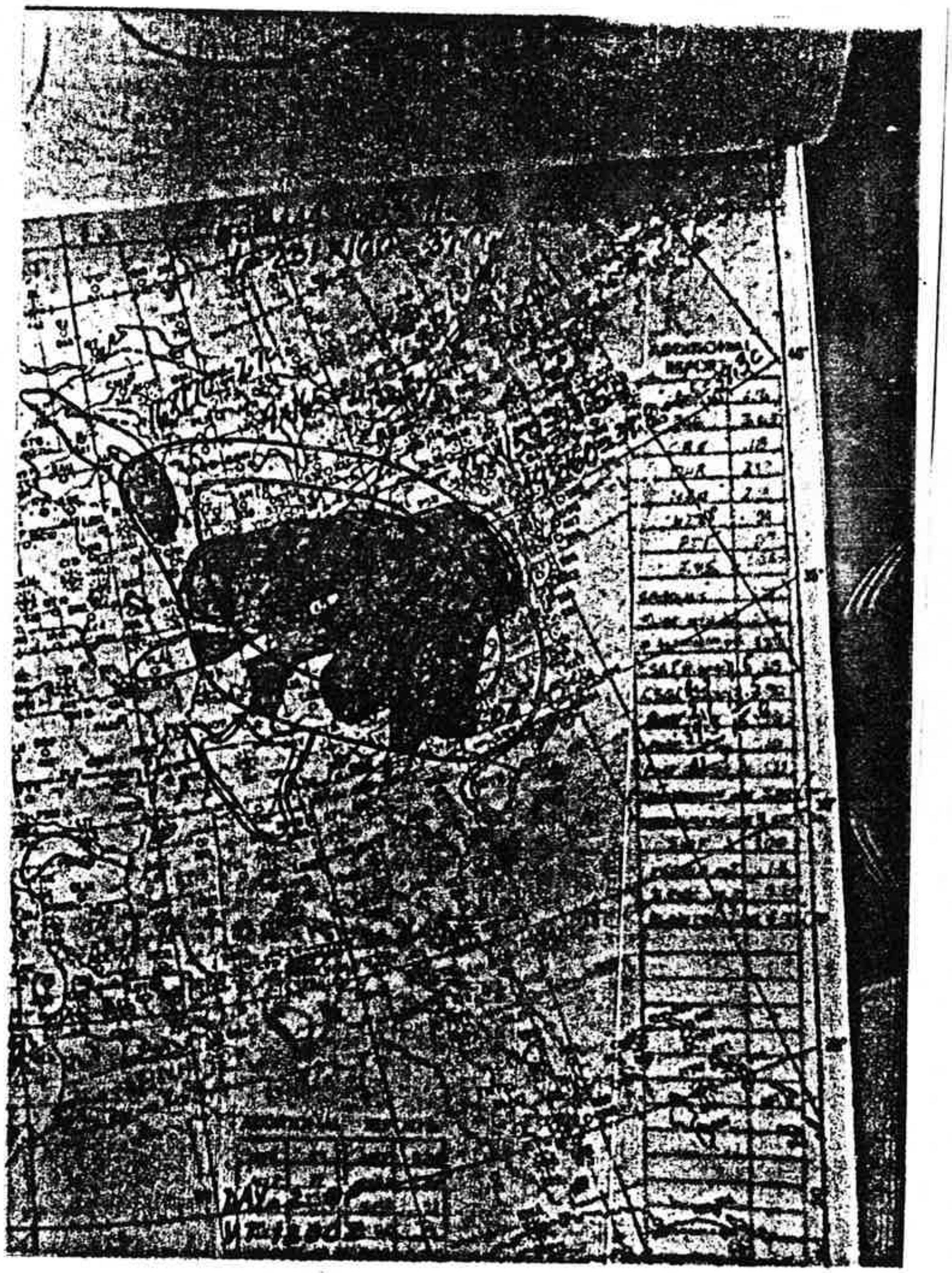
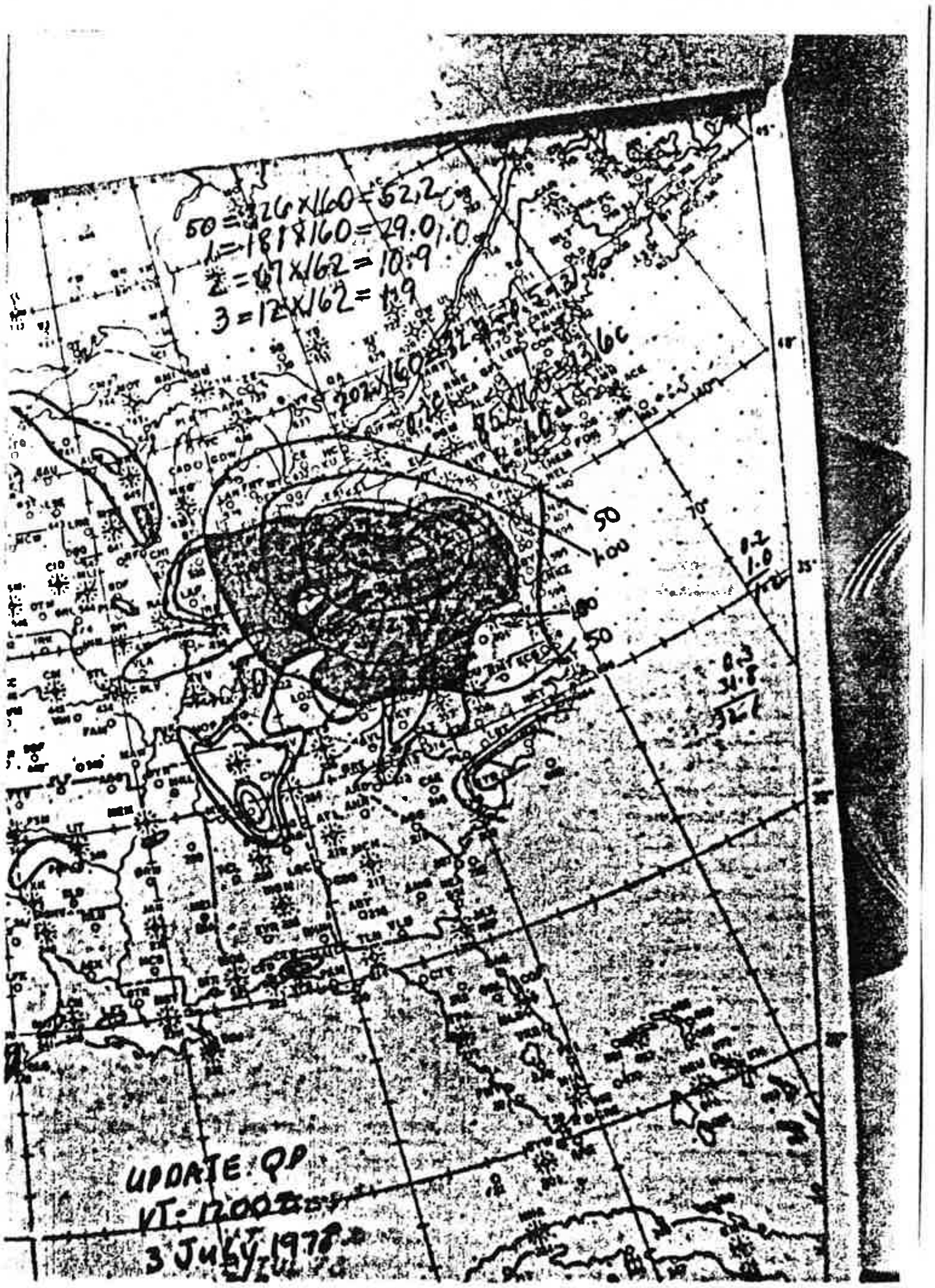


Figure 6



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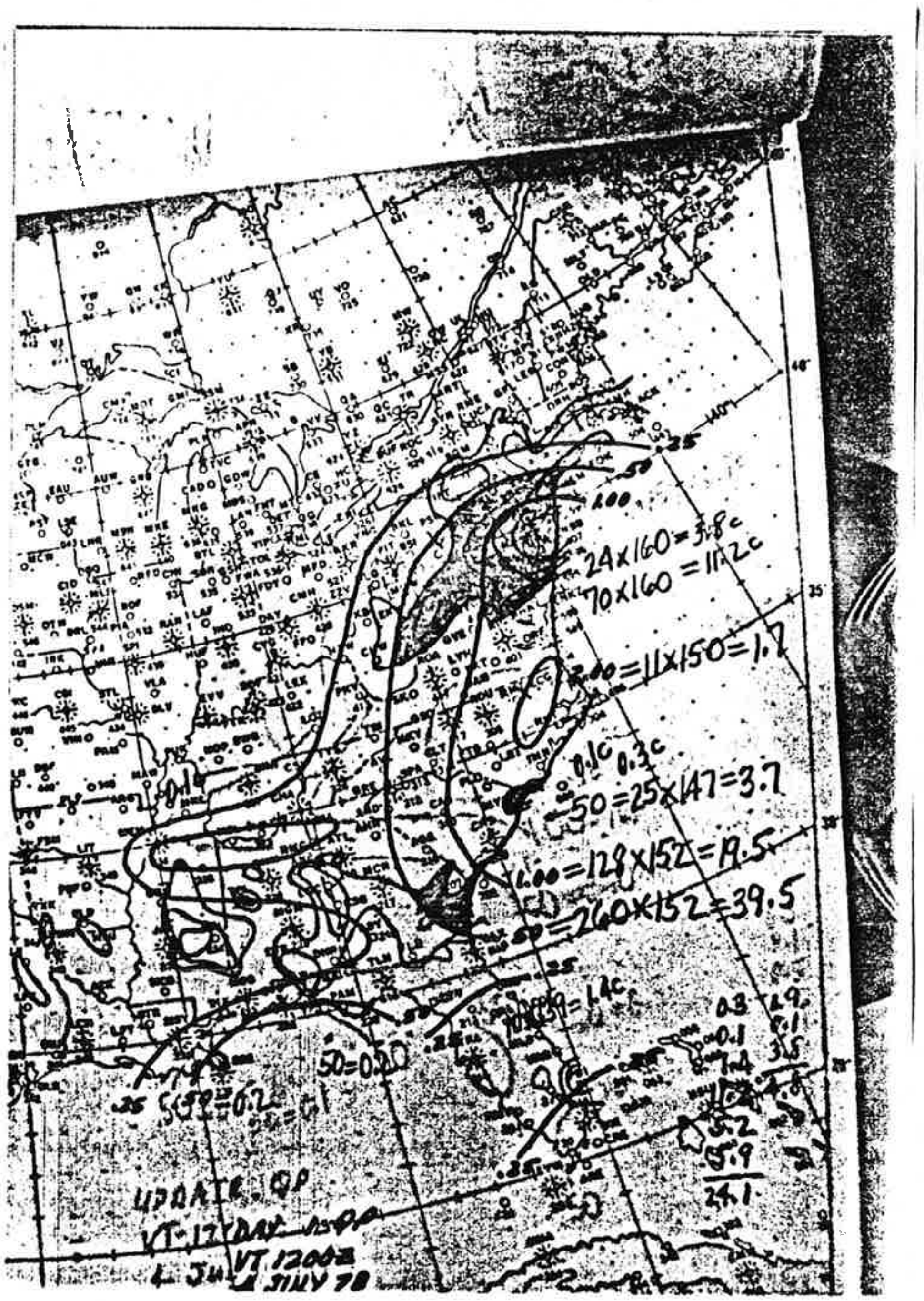
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70x160=11.2c
=11x150=1.7
50=25x147=3.7
1.00=128x152=19.5
=260x152=39.5
50=0.20
UPDATE QP
VT 1200Z

Figure 8

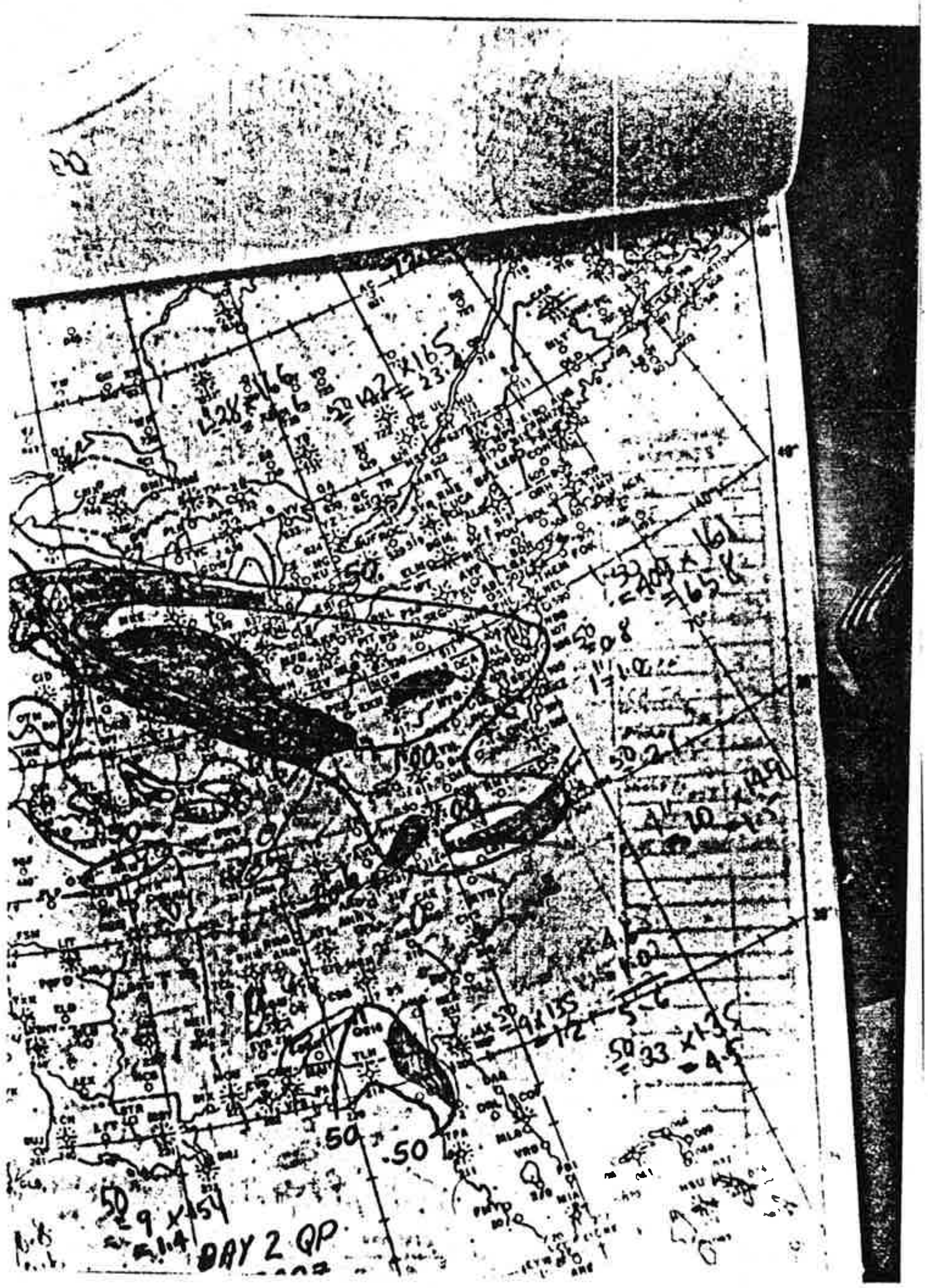

Figure 9

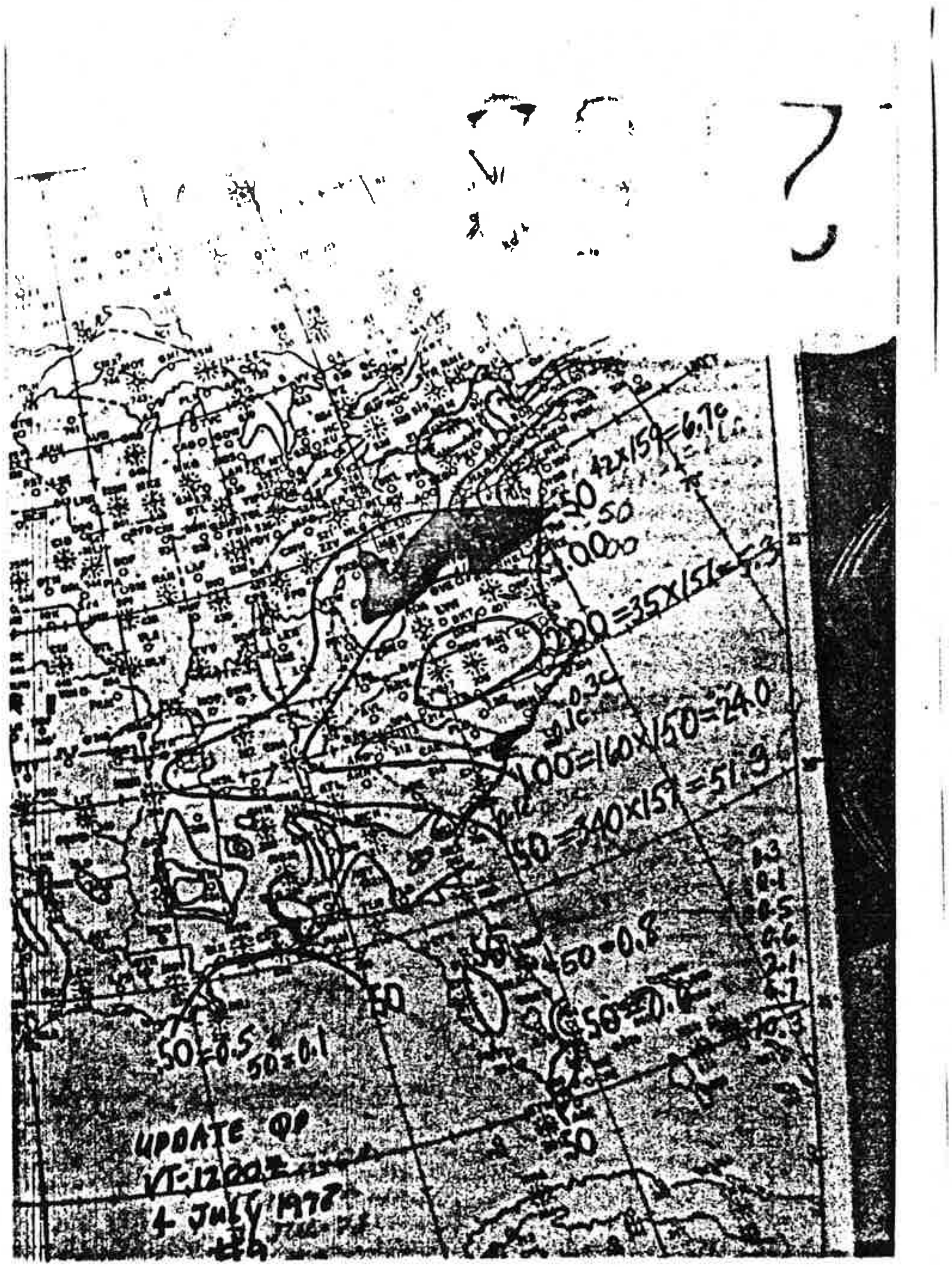

Figure 10

FLOOD FORECASTING JULY 1978

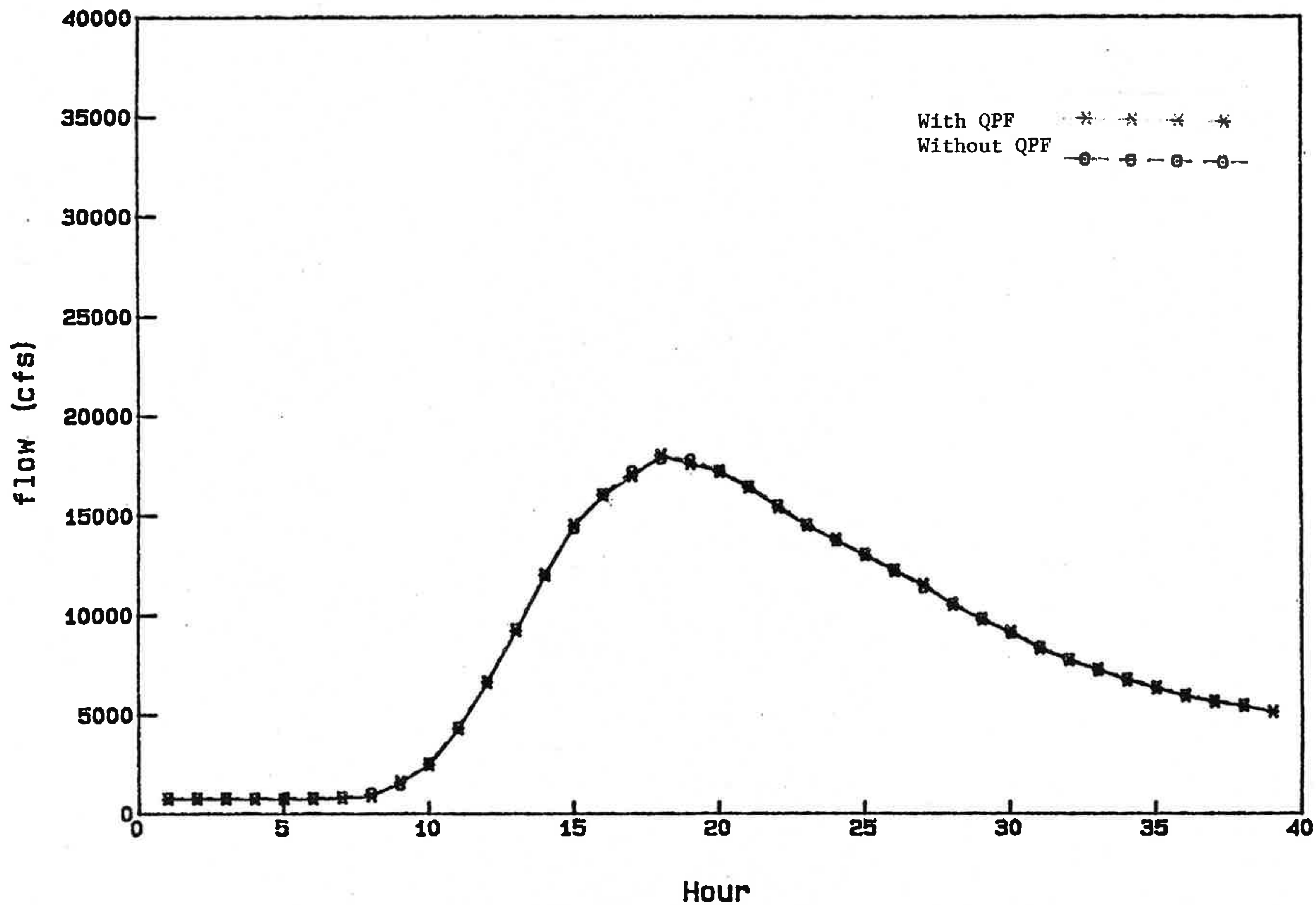

Figure 11

FLOOD FORECASTING AUGUST 1955

rms error

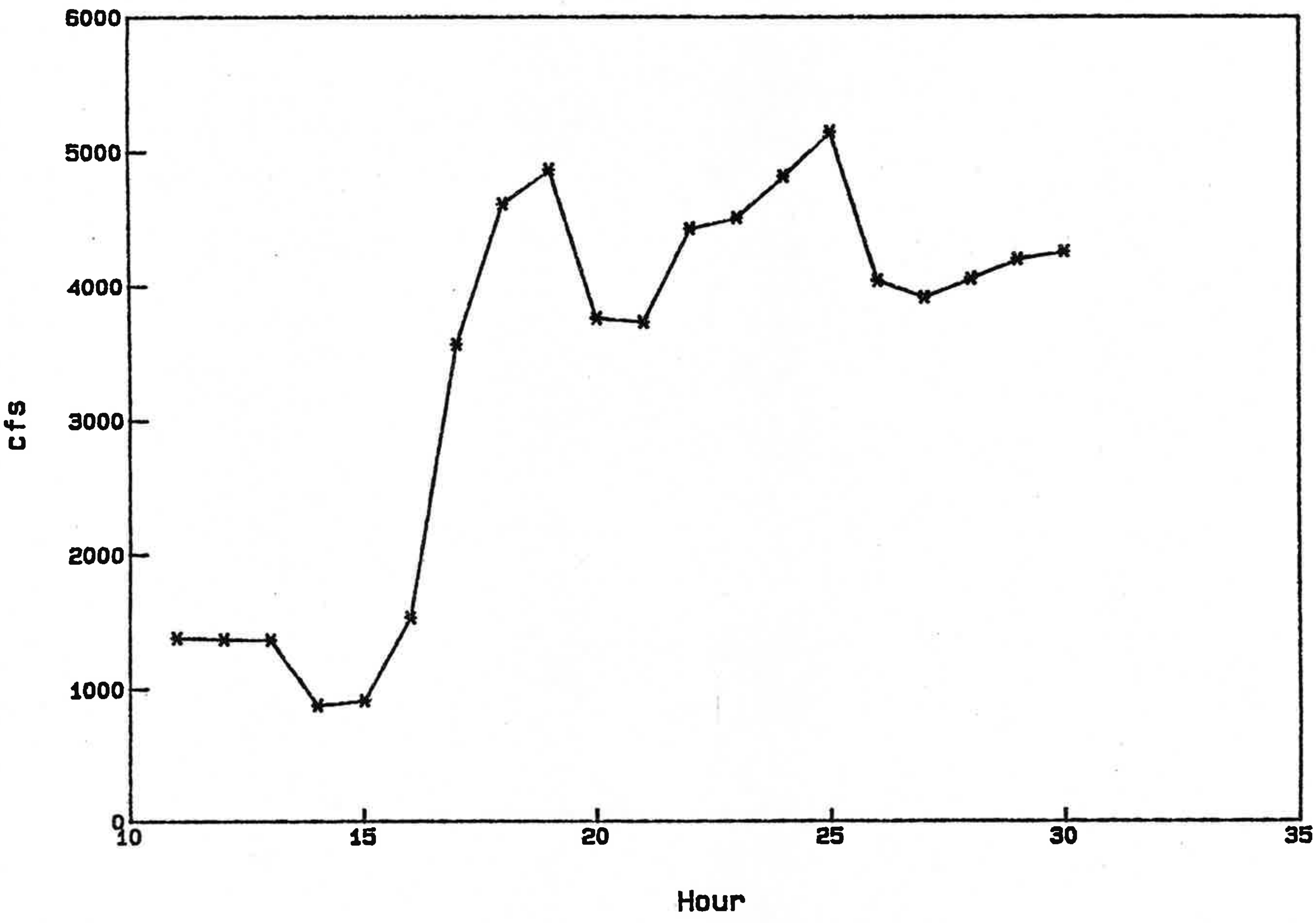

Figure 12

FLOOD FORECASTING AUGUST 1955

forecast for hours 14-16

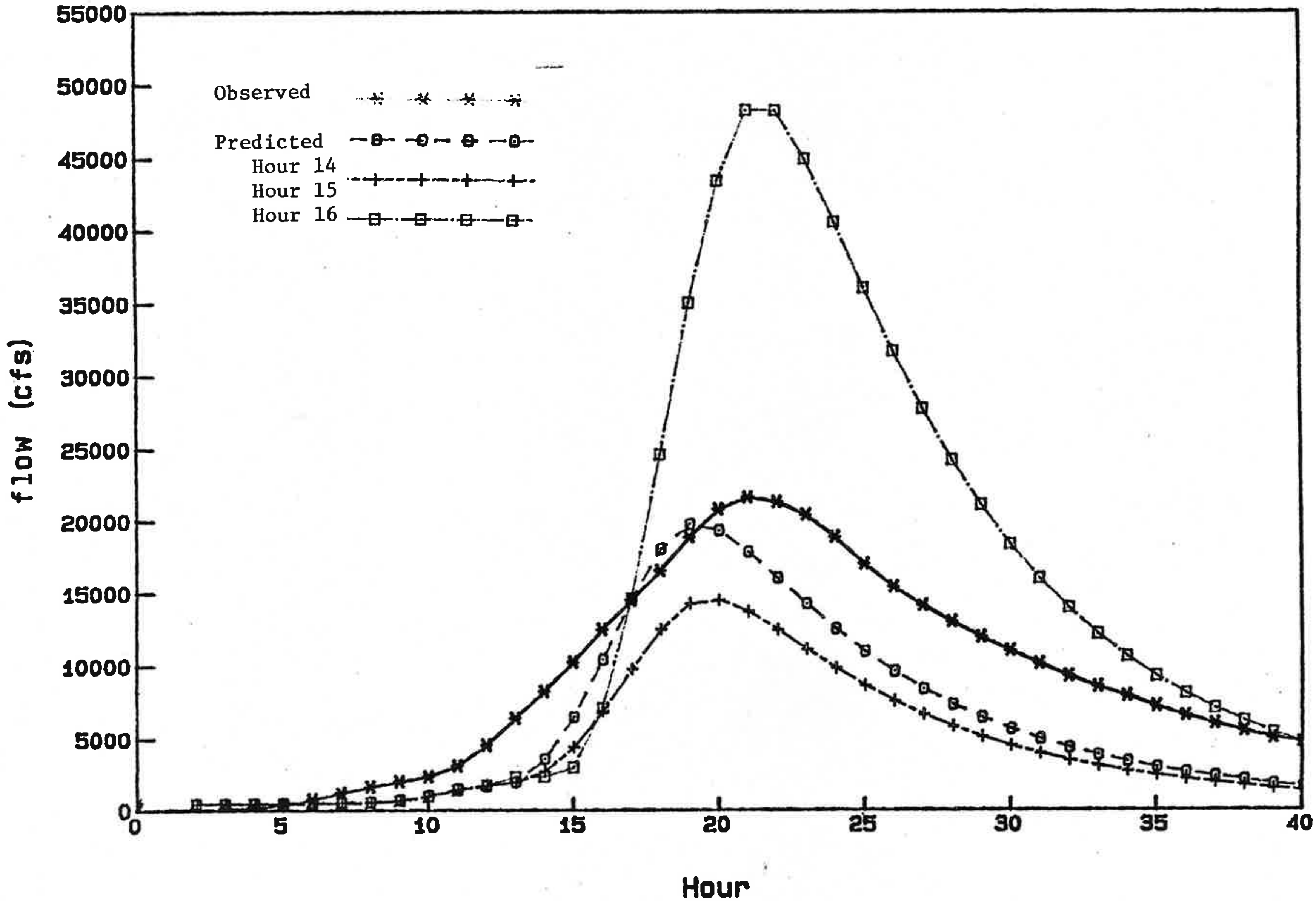

Figure 13

FLOOD ESTIMATION JULY 1978
rms error
with QPF

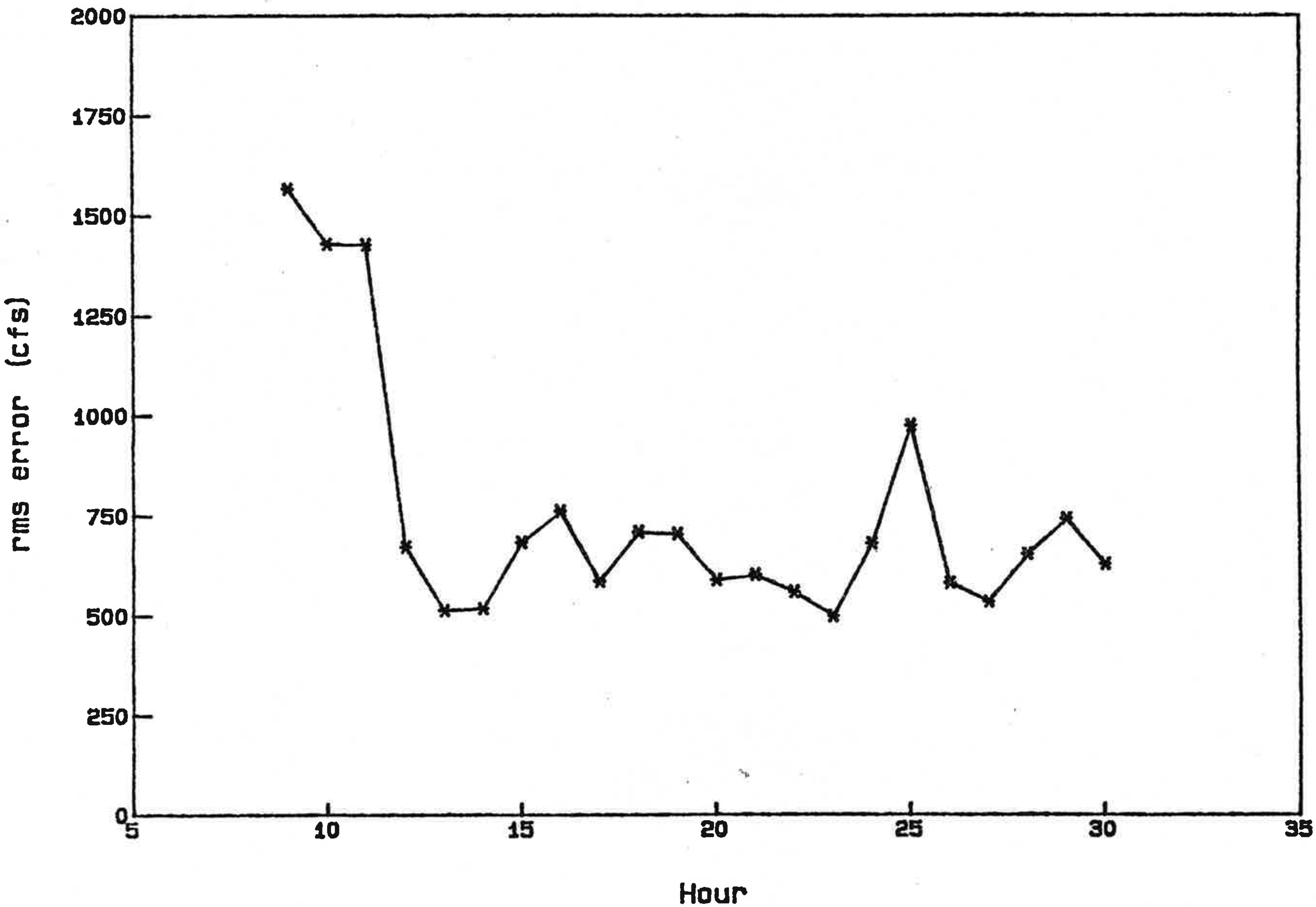

Figure 14

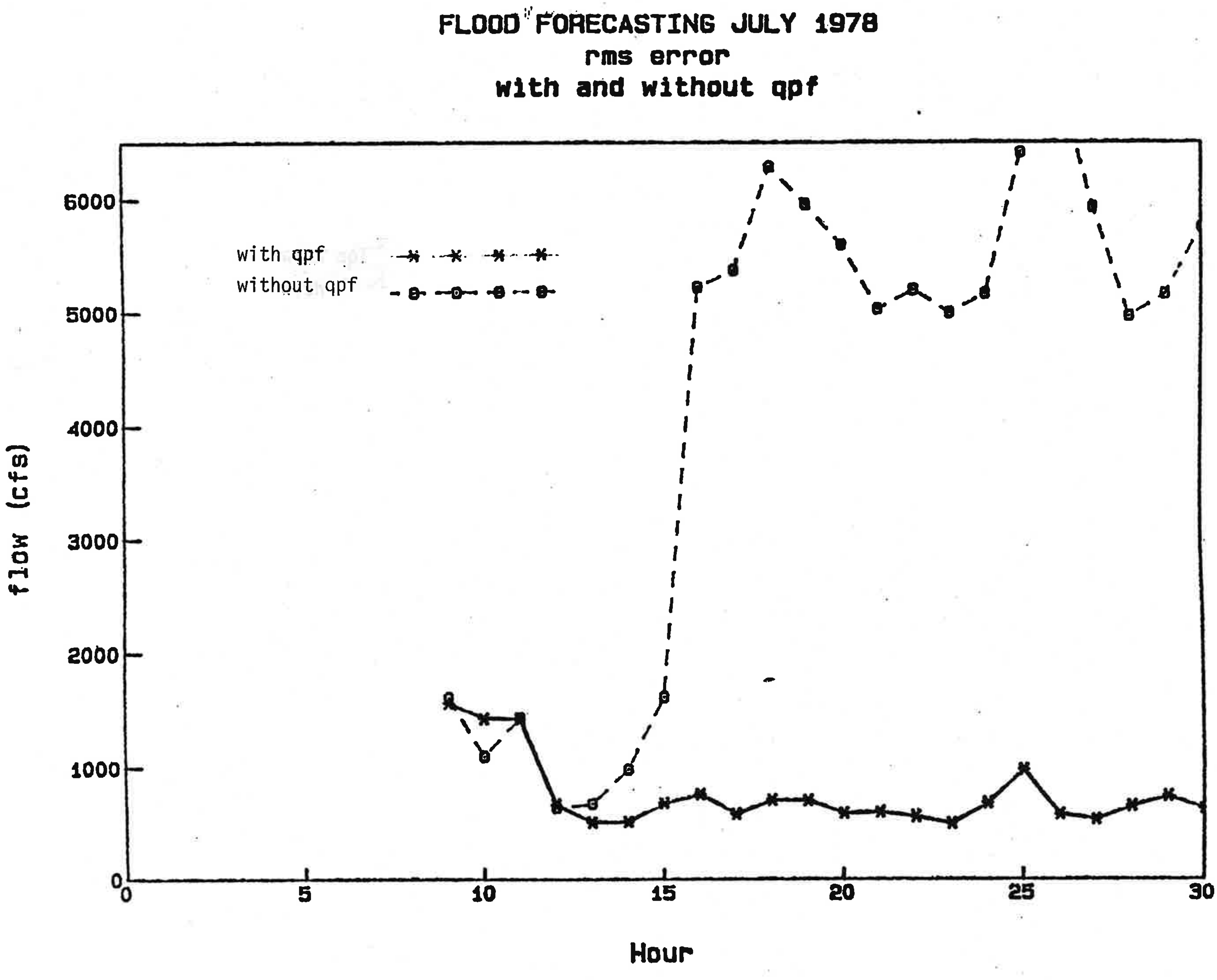
FLOOD FORECASTING JULY 1978
rms error
with and without qpf
with qpf
without qpf
6000
5000
4000
3000
2000
1000
0
flow (cfs)
0
5
10
15
20
25
30
Hour

Figure 15

FLOOD FORECASTING JULY 1978
forecasts from hours 11, 12, and 13
with QPF

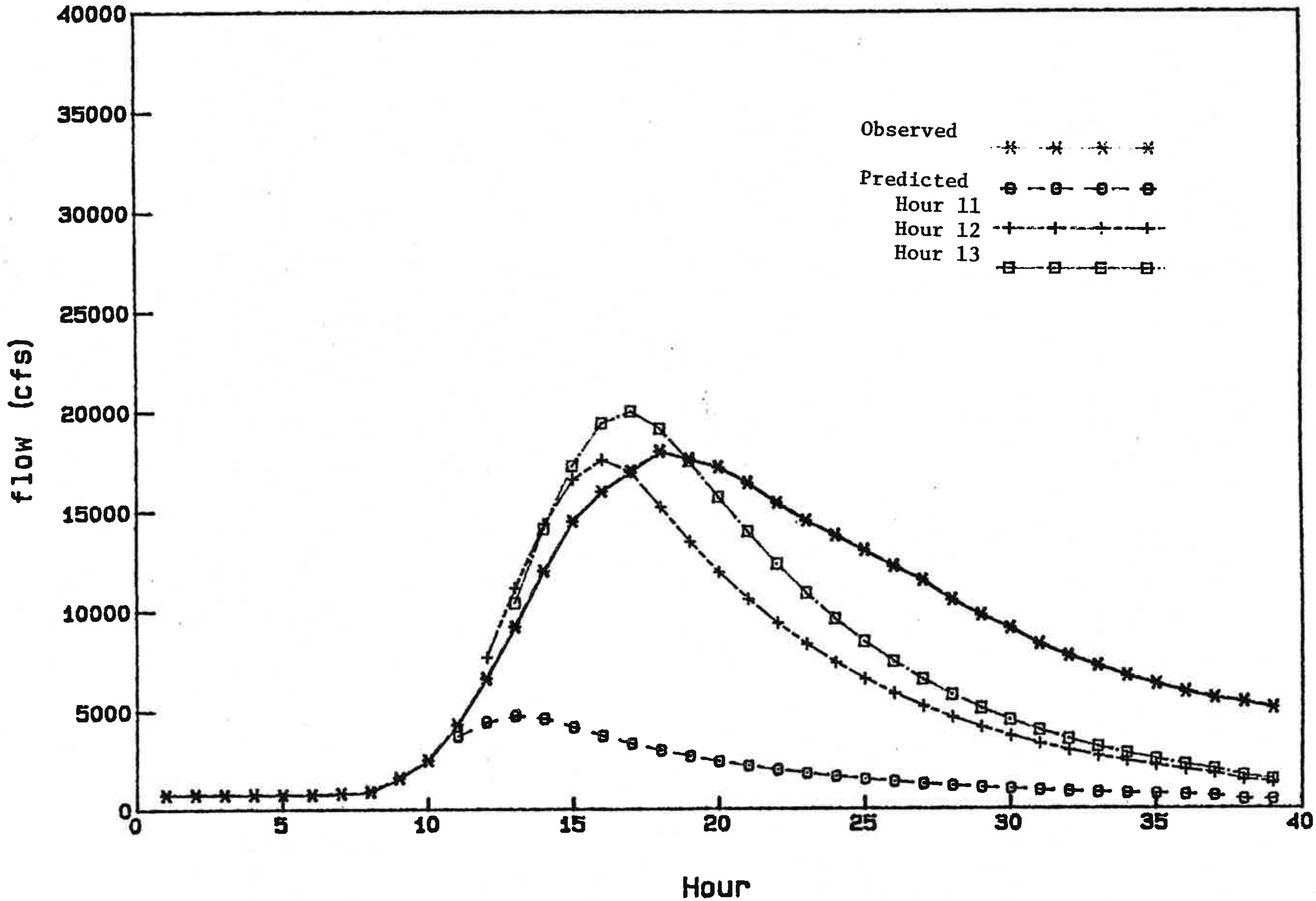

Figure 16

FLOOD ESTIMATION JULY 1978
coefficient of efficiency
with QPF

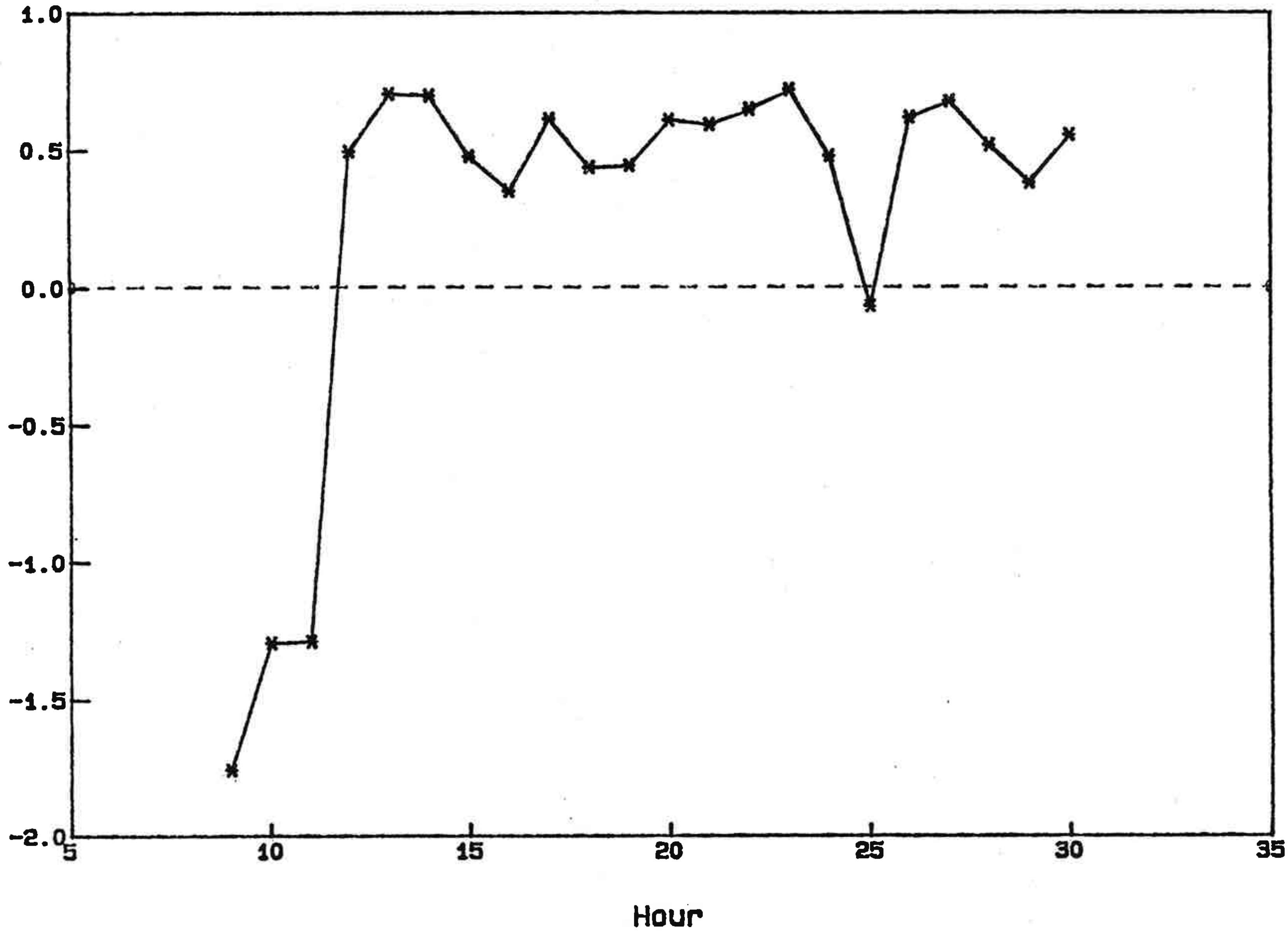

Figure 17

FLOOD FORECASTING JULY 1978
coefficient of efficiency
with and without QPF

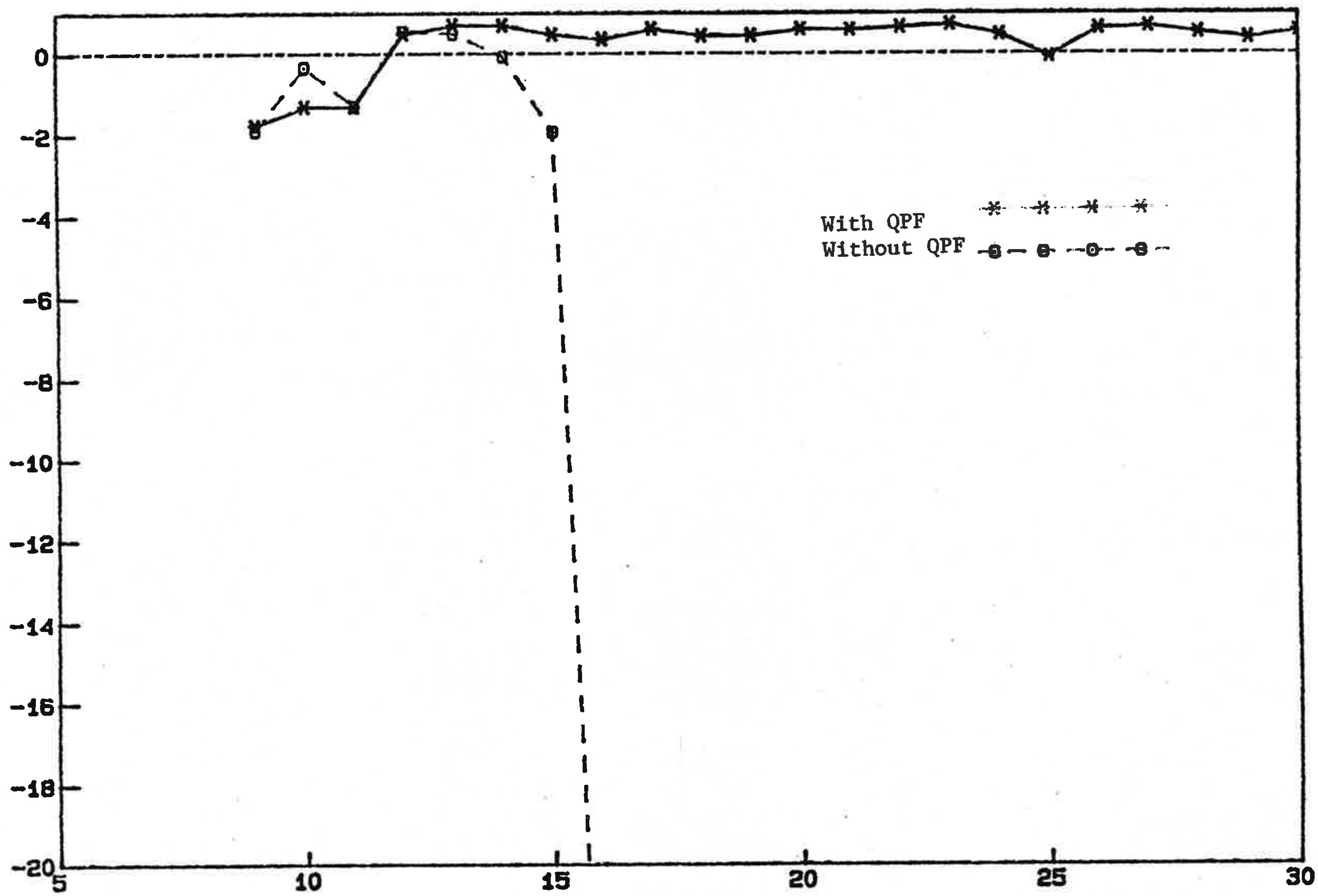

Figure 18

FLOOD FORECASTING JULY 1978
coefficient of persistence
with and without QPF

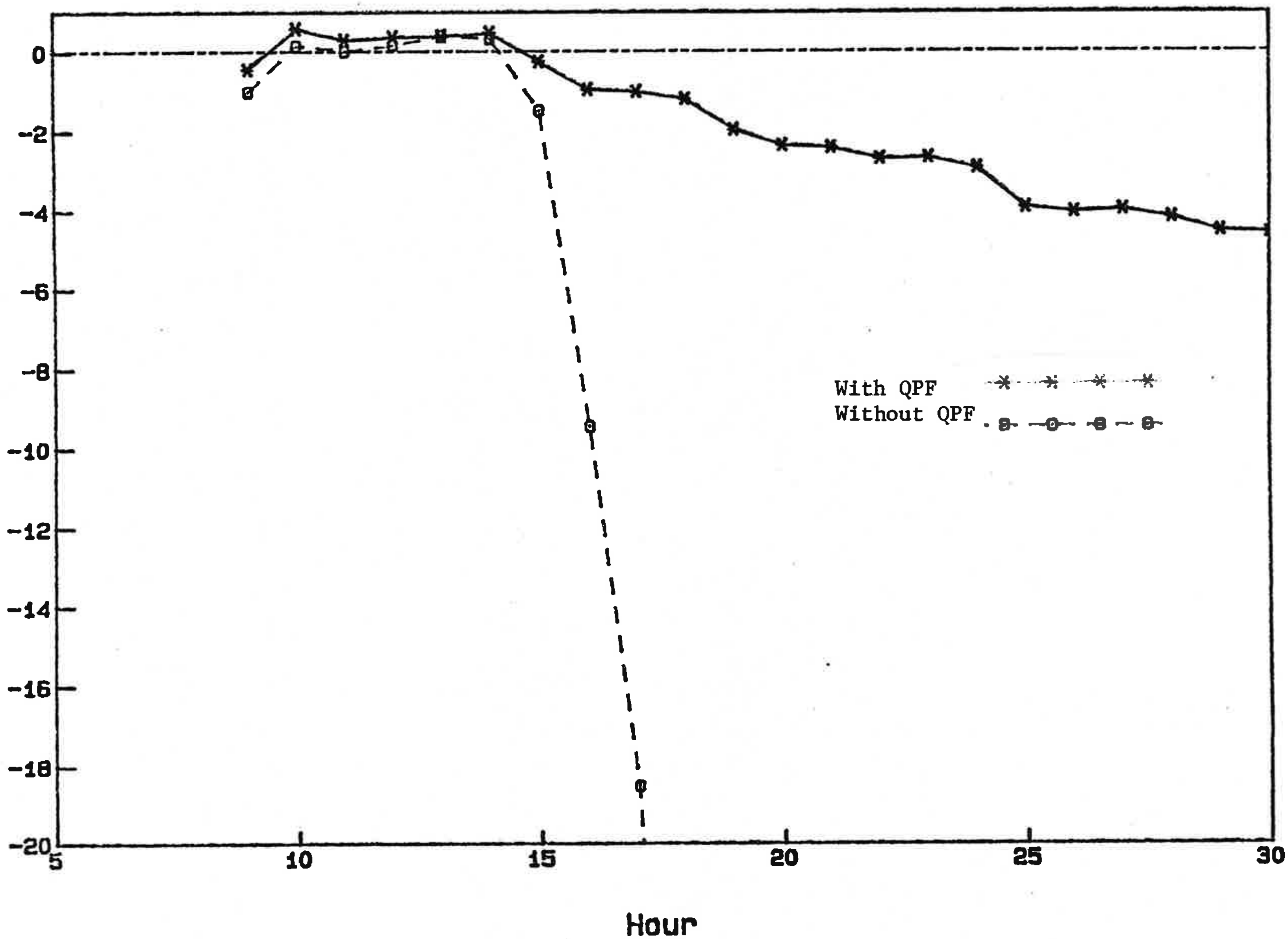

Figure 19

FLOOD FORECASTING JULY 1978
forecast for hour 24
with QPF