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DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

IMPROVEMENT OF HYDROLOGIC SIMULATION BY UTILIZING OBSERVED DISCHARGE AS AN INDIRECT INPUT
(COMPUTED HYDROGRAPH ADJUSTMENT TECHNIQUE--CHAT)

Silver Spring, Md.
February 1979

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NWS HYDRO 14	National Weather Service River Forecast System Forecast Procedures. Staff, Hydrologi Research Laboratory, December 1972, 7 chapters plus appendixes A through I. (COM-73 10517)
NWS HYDRO 15	Time Distribution of Precipitation in 4- to 10-Day Storms--Arkansas-Canadian River Basins. Ralph H. Frederick, June 1973, 45 pp. (COM-73-11169)

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IMPROVEMENT OF HYDROLOGIC SIMULATION BY UTILIZING OBSERVED DISCHARGE AS AN INDIRECT INPUT

(COMPUTED HYDROGRAPH ADJUSTMENT TECHNIQUE--CHAT)

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ABSTRACT. A computerized technique is presented whereby the output of a continuous conceptual hydrologic model is adjusted in real time to agree with the observations of discharge. Since the discharge generated by the model in response to a moisture input is dependent upon the current values of the state variables of the model, the procedure also adjusts the state variables to correspond to the output. The technique is applicable to outflow from headwater catchments during runoff events that result from liquid precipitation. Its approach is to make adjustments, iteratively and simultaneously, to the precipitation and the shape of the unit graph until the model produces a simulation that agrees, within reasonable limits, with the discharge observations. Examples of the performance of the procedure under a variety of hydrologic conditions are included.

1. INTRODUCTION AND BACKGROUND

River forecasting is a process in which hydrologic models, using meteorological variables as their inputs, are used to compute streamflow hydrographs for a period into the future. Such a computed hydrograph, or simulation, is continuous from the time the meteorological observations are made up to, and probably beyond, some critical time in the future. In flood forecasting that critical time may be the time of the crest or the time some lesser but significant stage is reached. During the interim, which may be as short as a few hours, or as long as several weeks, the forecaster normally has available a number of observations of the quantity he has computed, stage or discharge. He has the opportunity to compare the observed quantities with the values indicated by his simulation at the times the observations were made. The comparison almost always discloses differences, sometimes very large ones. The next step in the forecasting process is to somehow revise, or adjust, the simulation so that it agrees with the observations, and such an adjustment normally has some effect on the portion of the simulation that defines the response of the river during the critical time period in the future. The hydrologic simulation, revised on the basis of observed river stage or discharge, is what constitutes the forecast. Thus, observed river stage is normally one of the inputs to a forecast, but it is not an input to the hydrologic model since it has no effect on the output of that model.

The problem of adjusting computed hydrographs to agree with river observations has existed ever since river forecasting activities began. Prior to the early 1960's, the computations involved in river forecasting were done manually. The computed hydrograph was normally displayed as a hand-drawn curve on a sheet of cross-section paper. The observations were plotted on the same sheet and the adjustment process consisted of sketching in a revised hydrograph that coincided with the observations. The portion of the revised hydrograph subsequent to the time of the latest observation was based in part on the computed graph but could not, of course, be exactly equal to it. While the making of the adjustment was a very simple procedure, the decision as to how to make the adjustment was not simple. It was, of necessity, a highly subjective process and in cases where the discrepancies were large, demanded a high degree of skill and judgment from the forecaster.

When the practice of having computers perform the mathematical computations involved in forecasting began, the adjustment problem became a bit more complicated. There appeared to be two alternatives available. The first, which has come to be known as "manual" adjustment, consists of the forecaster viewing some sort of machine-produced display, which shows both the computed hydrograph and the observations, then making a subjective decision as to how the hydrograph should be adjusted, and instructing the computer to make such an adjustment. Thus, with this alternative, the decisions concerning adjustments are made in precisely the same manner as in a wholly manual operation, and the only additional programming required is a relatively simple routine to permit the forecaster to input his adjustment decision and have it executed.

The second alternative, called "automatic" adjustment, consists of programming the computer to make the adjustment decisions and then carry them out. This involves no human intervention whatsoever. The question of whether or not a computer can be programmed to satisfactorily model the human thought process involved in such decisions is highly debatable and has been debated at length over the years. Suffice it to say that the adjustment routines that have been devised and used for this purpose have been, almost without exception, rather simple "blending" procedures that gradually merged the partial observed hydrograph into the computed graph in a pre-determined manner and without any regard for the condition that caused them to differ in the first place.

In computerizing a river forecast operation, the decision as to whether to make the adjustments manually or automatically must be based on the answers to two questions. First, can a suitable automatic technique be devised and programmed; second, should this be done by computer rather than manually. With the type of hydrologic models used by the National Weather Service (NWS) prior to the early 1970's (A.P.I.-type rainfall-runoff analysis), the answer to the first question was probably "no," thereby rendering the second question superfluous. If the answer to the first question were in fact "yes," the second question might be difficult to answer. The making of such decisions manually involves rather complex mental processes, but they are not very time consuming. There is no question that any computerized forecast operation must be designed in such a way as to permit the forecaster to monitor various steps in the process rather than simply observe the final result. Such monitoring helps him to assess the nature of the situation at hand and to interpret the simulations that the computer produces. Since provision for such monitoring must be made, there is no compelling reason not to also provide for actual intervention by the forecaster at any step in the process.

The adoption by the NWS in 1971 of continuous conceptual hydrologic models as the standard for forecasting casts an entirely different light on this matter. The decision to make the change was based on a number of factors, one of the most important being that the conceptual models provide an accuracy advantage over the API method. This advantage, when judged on the basis of statistical error summaries of long simulations, appears to be slight. Closer examination, however, reveals that the overall improvement results from vastly better accuracy being achieved in certain small portions of the simulation. That is, there are some hydrologic regimes and some types of events in which the conceptual models yield errors at least an order of magnitude smaller than those obtained with API. Thus, the adoption of conceptual models can be expected to make only a small difference in the average size of the discrepancy between computed and observed streamflow. The maximum, or extreme discrepancies a forecaster may expect to encounter, however, should be greatly reduced. Since the making of hydrograph adjustments is not particularly difficult when the discrepancies are small, the adoption of a model that greatly reduces the extreme simulation errors also simplifies the adjustment process. For this reason, it seems logical to conclude that while an acceptable computerized decision-making algorithm may have been an impossibility when the raw simulations were being made with an API-type model, it may well be possible to accomplish this when the adjustments are to be applied to the output of a conceptual model. Thus, in the present era of river forecasting, the answer to the first of the two questions is probably "yes."

In regard to the second question, the picture is also different since the adjustment of the simulated hydrograph to agree with the observations is no longer the only thing to be accomplished. The nature of the accuracy advantage achieved with a conceptual model has been explained. The reason for it has not, but that reason is that the conceptual model has a longer "hydrologic memory" than does the API system. That is, the state variables involved in an API-type rainfall-runoff relationship are virtually unaffected by any hydrologic activity occurring more than about 1 month prior to the time in question and so the model cannot duplicate the type of event in which the actual response of the river is affected by occurrences several months earlier. The conceptual model on the other hand involves a rather complex soil moisture accounting system, which is capable of reflecting events that took place months or even years earlier. The Sacramento catchment model contains five state variables that represent the quantity of water in storage in various parts of the soil mantle. The discharge generated by the model in response to a moisture input is dependent upon the current values of these five variables. If at any time the simulated discharge is not in satisfactory agreement with that being observed, it follows that one or more of the state variables differ from their true values by an unacceptable amount. Because of the model's long memory, this condition may have a harmful effect on the accuracy of simulation of the <u>next</u> runoff event and should therefore be corrected along with the model output. The conclusion then is that in order to realize the accuracy of which a conceptual model is capable, it is necessary to adjust not only the model output to agree with the observed discharge but also to adjust the state variables to correspond to the output. Any procedure that can accomplish this must obviously have a complexity comparable to that of the model itself, and it is therefore not realistic to think in terms of executing the procedure manually. Since the procedure requires voluminous computations, the answer to the second question is also in the affirmative.

What is required then for use with conceptual forecast models is a computerized procedure that adjusts the state variables of the model in such a way that they produce a model output that agrees, within reasonable limits, with the observed discharge. Such a procedure, called CHAT (Computed Hydrograph Adjustment Technique), is being developed and is the subject of this technical memorandum. The two requirements that the procedure must fulfill are: the soil moisture accounting variables be adjusted along with the output and the adjusted output be at least as good as that which might be arrived at subjectively by a skilled human forecaster.

2. STATUS OF RESEARCH

The adjustment of computed hydrographs under all conditions encountered in a river forecasting operation requires the capability of dealing with all of the hydrologic conditions and situations that occur in a river system. The requirements for the technique as described in the previous section and the method of approach to be described in the next section indicate the definition of four problem areas and the development of different but similar techniques applicable to each. These four areas are associated with four phases of research as follows:

Phase 1. Development of an adjustment technique applicable to catchment outflow during runoff events resulting from liquid precipitation only.

Phase 2. Development of an adjustment technique applicable to catchment outflow during runoff events in which snowmelt is involved.

Phase 3. Development of an adjustment technique applicable to catchment outflow during low-water periods.

Phase 4. Development of an adjustment technique applicable to points in a river system that are not at the outlets of individual catchments.

Research work to date has been concerned only with the phase 1 problem, and the method presented in this technical memorandum is intended to be applicable only to the phase 1 problem. In chapter 7, "Suggestions for Future Research," some thoughts concerning possible solutions of the phase 2, 3, and 4 problems are presented.

The solution to the phase 1 problem that is described in subsequent sections, while not presented as an interim version, at the same time is not presented as a completely perfected technique either. The distinction lies in the fact that the authors view this technique as workable and ready for immediate operational use (without further planned research) but with full realization that modifications and improvements to the procedure will undoubtedly evolve from extended use in the field.

3. THEORY

When a simulated hydrograph is compared with observed values of discharge, the discrepancy noted is the combined effect of four error sources:

1. Errors in model input data
2. Errors in model parameters
3. Errors in model structure
4. Errors in observed discharge

The basic concept of CHAT is that if the true values of the input data were known and were applied to the model, then the discrepancy in the output would result only from error types 2, 3, and 4 and that if this could be accomplished two conditions would then exist. First, the values of the intermediate state variables would be about as close to their true values as the model is capable of making them and therefore so close that the potential accuracy of the model could be realized in the simulation of a future runoff event. Second, the discrepancy resulting from error types 2, 3, and 4 would be small enough that it could be either ignored or reconciled by a "blending" algorithm. These contentions involve the assumptions that the model parameters being used have been carefully determined and are close to their true values and that the errors in the observed discharge are small compared to other errors in the modelling procedure. The second contention involves the additional assumption that the model structure is a good enough representation of the physical process that it cannot in itself be responsible for gross errors in simulated discharge. It was stated in the "Introduction and Background" section that an automatic adjustment technique for use with an API forecast model may be an impossibility but could be feasible when the simulations are made with a conceptual model. That statement relies heavily on this assumption. An API-type model is capable of yielding gross errors even with perfect parameters and perfect data. Hopefully, the conceptual model is not. There is, however, an exception to this which must be recognized and dealt with, and that is the manner in which the model converts runoff volumes to the ordinates of a discharge hydrograph. This is accomplished through the use of a unit hydrograph, which models a nonlinear time variant process with an algorithm which is both linear and time invariant. There are available, of course, model modifications that make it possible to apply a degree of flexibility and nonlinearity to the response function which the unit hydrograph models. The fact remains, however, that even if the unit hydrograph, which is a model parameter, could be evaluated exactly, it would still represent an average runoff distribution that may differ greatly from the distribution in a specific event. This inability of the model to duplicate a hydrograph resulting from an unusual runoff distribution is a limitation of the model structure and can be the source of large discrepancies between the simulated and true hydrographs. It follows then that in such cases there must exist a unit hydrograph, somewhat different from the average, that, if used by the model for the specific event, would produce a simulated hydrograph in close agreement with the observed. CHAT, as will be shown later, has the capability of detecting such anomalies and modifying the unit hydrograph accordingly, thus eliminating the gross discrepancy that would otherwise result.

The approach used to apply this concept is to make adjustments, iteratively and simultaneously, to both the input data and the shape of the unit hydrograph until the model produces a simulation that is in satisfactory agreement with the discharge observations. "Satisfactory agreement," in this context, means that the discrepancy is small enough to be reasonably attributable to error types 2, 3, and 4 as defined above but not including gross errors resulting from large differences between the actual runoff distribution and that assumed by the unit hydrograph. For the phase 1 study, the only input data types involved are liquid precipitation and potential evaporation. Since the effect of the errors in evaporation data during runoff events is thought to be negligible, only the precipitation is adjusted. It might be noted at this point that the precipitation input to the model consists of areal means (MAP) rather than point amounts. These means are normally determined by analyzing the point precipitation measured with rain gages. While sizeable simulation errors can be attributed to the precipitation input, they originate mostly in the conversion of point amounts to areal means rather than from errors in point measurement.

When satisfactory agreement has been achieved by adjusting both the precipitation and the unit hydrograph, five conditions are assumed to exist:

1. The adjusted precipitation data are a closer approximation to the true precipitation than was the original data derived from rain gage observations.

2. The adjusted unit hydrograph expresses the runoff distribution of the event more closely than does the average unit hydrograph derived from historical records.

3. The values of the state variables are closer approximations to the true values than those that would be generated by applying the original precipitation data to the model.

4. The agreement between the simulated hydrograph and the observed discharge is close enough that the difference can either be ignored or resolved by "blending."

5. The portion of the simulated hydrograph subsequent to the time of the last discharge observation contains all available information concerning the event and does in fact constitute a forecast.

To truly achieve these five conditions requires that the adjustments be made in a manner consistent with the underlying rationale. The details of making the adjustments are explained in subsequent sections. To appreciate the reasons for performing the operations in the manner described requires the understanding of a number of subtle but extremely important aspects of the technique.

1. CHAT utilizes an objective function as an indicator of the extent of the disagreement between simulated and observed discharge. Constraints are used to limit the values that may be assigned to the decision variables, precipitation and the unit hydrograph adjustment coefficients. Thus, CHAT resembles a conventional optimizing procedure. Unlike conventional optimizing however, CHAT does <u>not</u> seek to minimize the objective function subject to the constraints on the decision variables. Rather, it reduces the objective function to an acceptable value while making the smallest possible changes in the decision variables.

2. Adjustments applied to the unit hydrograph affect the simulated hydrograph but have no <u>direct</u> effect on the soil moisture accounting state variables. They do, however, affect these state variables indirectly by influencing the adjustments that are made to the precipitation input.

3. In most cases, it would probably be possible to make precipitation adjustments that would reduce the objective function to a value considerably smaller than that which is considered acceptable. To do so would be to adjust the precipitation in order to minimize discrepancies that originate from other factors. This would produce values of adjusted precipitation, values of state variables, and a future simulation that would be further from their true values than those that result from stopping the adjustment procedure at the appropriate point.

4. CHAT will not necessarily always make adjustments to the input data. If, at any point in the forecasting process, the difference between the observed discharge and the simulation resulting from the input data as adjusted at the previous forecast time is within limits, CHAT will recognize this condition and make no adjustments.

4. COMPONENT PARTS

The application of the CHAT adjustment procedure involves six mathematical algorithms in addition to the hydrologic model itself. These can be thought of as component parts of the CHAT package. Each has been coded in the form of a computer subroutine and the adjustment procedure is accomplished by calling those subroutines and that representing the hydrologic model. The six parts and their associated subroutine names are:

1.	Objective function	OBJEC
2.	Tolerance	TOL
3.	Unit hydrograph adjustment	WARP
4.	Adjustment strategy	STRAT
5.	Observed discharge interpolation	INTERP
6.	Blending routine	BLEND

In this section, the rationale and mathematical formulations involved in each of these parts are discussed. Listings of the subroutines themselves appear in Appendix A.

Objective Function

The objective function is a numerical measure of the difference between a simulated hydrograph and a group of one or more discharge observations. It serves two purposes in the technique. First, during the iterative adjustment process, changes in the value of the objective function indicate whether the fit is improving or degrading. Second, when the objective function has been reduced to a pre-determined acceptable value, the "tolerance," the agreement between the observations, and the computed hydrograph is considered satisfactory and the adjustment process ceases.

The function compares an array of computed discharges, spaced 6 hours apart, with a corresponding array of observed discharge values. The function involves the observed and computed discharge at each 6-hour ordinate, up to the latest observed discharge. If the latest observation is not at the time of a 6-hour ordinate, the function involves all ordinates up to the one immediately preceding that observation and in addition that observation and the corresponding computed discharge, which is obtained by linear interpolation.

The "observed" discharge values are, of course, in most cases, obtained by applying stage observations to a stage-discharge relationship. In practice, such observations often do not exactly coincide with the 6-hour ordinates of the computed discharge array and missing observations are common. The observed discharge interpolation procedure (subroutine INTERP) computes a matching array of observed discharge ordinates based on whatever randomly spaced observations happen to be available.

The basic equation for the objective function is:

$$OF = \frac{\sum_{L=1}^{NOB} WD(L) \left[\frac{WT(L)DQ(L)+WM(L)QO(L)}{2}\right]}{\sum_{L=1}^{NOB}} \qquad (4.1)$$

where:

NOB is the number, in the discharge arrays, of the ordinate at the time of the latest observed discharge. If the latest observation is not at the time of a 6-hour ordinate, then NOB is the number of the ordinate immediately preceding that observation.

WD(L) is a weight related to the time interval between ordinate, L, and the latest observation. That is, the most recent ordinates are considered more significant than the earlier ones. The weight is given by:

$$WD(L) = (L/TLO)^{EX2}. \qquad (4.2)$$

TLO is the time of the greatest observed discharge, referred to the array indexing scale. During the rising limb of the hydrograph, this is usually the latest observation. If this discharge value coincides with an ordinate, then TLO is an integer. If it is the largest observation and does not coincide with an ordinate, then TLO = NOB plus some amount less than unity. EX2 is an exponent that permits the variation of the weight with time to be made nonlinear. The research indicates that an appropriate value for EX2 is 2 or 3.

The rationale behind considering the most recent ordinates more important than earlier ones involves the concept of the forecast or future portion of the simulated hydrograph being an extension of the earlier portion. While both portions are generated by the model in the same way, the earlier portion is compared with, and directly controlled by, the observed discharge. The future portion is controlled only indirectly.

To avoid unrealistic discontinuities between the observed partial hydrograph and the extension part of the simulation and thereby reduce the chance of having large errors in the forecast, it is necessary to achieve rather close agreement in the vicinity of the transition.

This rationale applies only on the rising limb of the hydrograph. Once past the peak, the procedure is more concerned with adjusting the volume under the entire hydrograph. Therefore, ordinates further down the recession are not necessarily any more significant than earlier ones. For this reason, the value of WD(L) becomes unity at the peak and remains unity for all L>TLO.

DQ(L) is the absolute value of the difference between the observed and computed discharge at ordinate, L.

WT(L) is a timing weight. It reflects the fact that discharge observations are subject to errors in time as well as magnitude and that, in addition, the structure of the model precludes its being able to achieve a fine time discrimination in the output. Thus, in a steep portion of the hydrograph, it is possible to have large values of DQ(L) when the only real disagreement between the simulation and the observations is a small timing error. The timing weight prevents such discharge discrepancies from contributing heavily to the objective function. The weight is computed by determining the value of DT, the time interval between ordinate L, and the nearest simulated discharge equal to the observed discharge at ordinate, L. Then,

If $DT \leq 3$ hours, $WT(L) = 0$

If $DT \geq 12$ hours, $WT(L) = 1$

If $3 < DT < 12$, $WT(L) = (DT-3)/9$.

In order for a WT(L) of less than unity to be used, it must result from matching discharges at points where the two hydrographs have similar slopes. That is, if the observed hydrograph at ordinate, L, has a positive slope and if the segment of the simulated hydrograph in which the matching discharge is found has a negative slope, or if the reverse is true, then that matching discharge is ignored.

QO(L) is the observed discharge at ordinate, L.

WM(L) is a slope weight. Its purpose is to increase the objective function when the two hydrographs, at an ordinate, agree closely in magnitude but have vastly different slopes.

In Eq. 4.1, the product of WM(L) and QO(L) is added to the product of DQ(L) and WT(L). Thus, WM(L) must be computed in such a way that if the degree of mismatch expressed by the first product is the same as the degree of mis-match expressed by the second, then the two products will be of equal magnitude numerically. In regard to WT(L)DQ(L), the "worst case" situation might be thought of as that in which the discharge error is 100 percent of the observed discharge and WT(L)=1. In this case, the product is equal to the observed discharge, QO(L). This product is computed every 6 hours. Consequently, an equally serious slope mis-match would be the case in which the difference in slope of the two hydrographs is such that in 6 hours, they diverge by an amount equal to the observed discharge. In this case, the second product must be equal to QO(L) and thus, WM(L) must be unity. WM(L) is then given by:

$$WM(L) = ABS[(S_o - S_c)/QO(L)] \qquad (4.3)$$

but not greater than 1.0.

Where S_o and S_c are the slopes, in cms per 6 hours, of the observed and simulated hydrographs. The slopes, at each point, are computed in the manner described in regard to Subroutine INTERP (page 39). The slope at the last point on the observed hydrograph is, of necessity, computed as a straight line slope. The slope of the simulated hydrograph at the same point is, for the sake of consistency, computed the same way, even though simulated points later in time are available.

Note that the computation of WM(L) involves dividing by QO(L) and that in Eq. 4.1, WM(L) is multiplied by QO(L). This is not an unnecessary step since in the case where $(S_o - S_c)$ is greater than QO(L), the weight is "topped off" at unity.

Weight WM(L) is subject to one final adjustment. If, within 12 hours of the ordinate, the simulated hydrograph exhibits a slope equal to that of the observed hydrograph at the ordinate, then WM(L) is reduced in value. The formulation is identical to that used in computing weight, WT(L).

The objective function computed as described from Eq. 4.1 is valid only for the case in which the latest observed discharge is at the time of ordinate, NOB. If this is not the case, the contribution of the partial 6-hour period must be included and the function is computed by:

$$\mathrm{OF} = \frac{\sum\limits_{L=1}^{NOB} \mathrm{WD(L)} \left\{ \frac{\mathrm{WT(L)DQ(L)+WM(L)QO(L)}}{2} \right\} + \mathrm{PJ} \left\{ \frac{\mathrm{(WTLT)(DQLT)+(WMLT)(QOLT)}}{2} \right\}}{\sum\limits_{L=1}^{NOB} \mathrm{WD(L)} + \mathrm{PJ}} \qquad (4.4)$$

where:

WTLT	is the timing weight, WT, at the time of the last observation.
DQLT	is the absolute discharge difference, DQ, at the time of the last observation.
WMLT	is the slope weight, WM, at the time of the last observation.
QOLT	is the observed discharge at the time of the last observation.
PJ	is one-sixth of the time interval from ordinate NOB to the last observation. PJ must always be greater than zero and less than unity.

Eq. (4.4) is essentially the same as Eq. (4.1) but gives a weight of PJ to the last ordinate and weights of unity to all previous ordinates. It should be noted that the second term of the numerator of Eq. (4.4) is weighted not only by PJ but also by its value of weight, WD. This weight, however, must be unity at this point and hence does not appear in the equation. It should also be noted that the summation of weights WD in the denominator is from ordinate 1 to ordinate NOB and does not include the unit value of WD that occurs at ordinate NOB + PJ.

The rationale and formulations described above are intended to model, to some degree, the thought processes which a human forecaster uses in judging the seriousness of a disagreement between the rising limb of a simulated hydrograph and a group of discharge observations. The major objective in making such a judgement is to decide if a future portion (the peak) of the simulated hydrograph represents a valid forecast. After the peak has been observed, however, there is no forecast to make, with the possible exception of a recession forecast. CHAT however, as explained in Chapter 1, has a dual purpose: to adjust the simulation to produce an acceptable forecast and to come out of the runoff event with a set of values for the soil moisture variables which are closer to the true values than those which would be yielded by the "raw" simulation. To accomplish this latter purpose, CHAT keeps on working right down the recession.

When the entire hydrograph, or a major portion of it has been observed, it has been found that the use of a more statistically based error function to guide the adjusting process gives results superior to those obtained with the function described above, as that function embodies concepts appropriate to forecasting a peak as opposed to fitting an entire hydrograph. Consequently, the subroutine also computes the root mean square error of the 6 hourly discharges, RMS. Up to the time of the observed peak, the objective function is equal to the value computed from Eq. 4.1 or 4.4; when the time from beginning of the event to the present is greater than twice the time from the beginning to the peak, the objective function is equal to the RMS. In the intervening period, it is a weighted average of the two.

Since the RMS may be combined with the basic objective function and since it is compared with the tolerance, it must be computed in such a way that similar degrees of agreement will yield a basic objective function and an RMS of similar magnitude. Experience has shown that this may be accomplished by computing the true RMS and then multiplying it by 0.25.

The objective function then is computed as follows:

The basic value is determined from Eq. 4.1 or 4.4.

The RMS is computed as:

$$\mathrm{RMS} = 0.25\ \mathrm{SQRT}\left(\sum_{L=1}^{NOB} (DQ(L)^2)/NOB\right). \qquad (4.5)$$

If the last observation is a partial ordinate, it is included, suitably weighted.

Then, a weighting factor, WF, is determined:

$$WF = 2 - (PJ+NOB)/MPT \qquad (4.6)$$

but not less than zero nor greater than unity. PJ and NOB are as previously defined and MPT is the time of the peak on the array indexing scale.

Finally:

$$OF = (OF)(WF) + (RMS)(1-WF). \qquad (4.7)$$

Tolerance

The tolerance is the maximum value the objective function may have while representing a satisfactory agreement between the observed and computed hydrographs. As such, it is a quantity that must have the same dimensions as the objective function, and, in addition, the manner in which it is computed must be related to the manner in which the objective function is computed. The objective function is essentially a weighted mean discharge, and so the tolerance is also expressed in units of discharge. Its value is dependent upon two factors, the magnitude of the discharge that is contributing most heavily to the objective function and how far the runoff event has progressed at the time the computation is made.

The tolerance is related to discharge because both modelling errors and errors in discharge observations tend to increase in magnitude along with the discharge itself. Thus, if the tolerance is to be thought of as a measure of error types 2, 3, and 4 as defined in the section on "Theory," it must increase as the discharge increases.

As the runoff event progresses from the beginning of the rise, past the peak and on down the recession, an ever greater portion of the runoff can be thought of as being "observed." Typically, at the time the peak occurs, only about 35 to 40 percent of the runoff volume (upper level components) has passed the gage. When just half of the time from beginning of rise to peak has elapsed, the figure is 5 to 10 percent. It follows then that if an attempt is made to obtain a close fit early in the rise, based on only a small portion of the observed runoff, that the effect of observational errors and of imperfections in the method will be magnified. This is avoided by using a very large tolerance at the beginning of the rise and gradually "tightening" it as more of the observed hydrograph becomes available.

The tolerance is computed by the following equation:

$$\mathrm{TOL} = \frac{\mathrm{PCOB}}{\mathrm{WP}} \qquad (4.8)$$

where:

PCOB is a fixed percentage of either the latest observed discharge, QO(NOB) or QOLT, or of the average observed discharge up to that time, whichever is greater. The percentage to be used, expressed as the coefficient, PCENT, depends on the stability of the stage-discharge relationship. A typical value would probably be about 5 to 10 percent. Values of 0.05, 0.075, and 0.1 have been used in the investigation.

The middle value, 0.075, seems to give the best results. All cases that were studied have involved reasonably stable stage-discharge relationships. Normally, PCOB is based on the latest observed discharge up to a few intervals past the peak and then the average observed discharge begins to exceed the latest observed and becomes the basis for computing the tolerance.

WP expresses the relationship, in time, between the current time and the stage of development of the runoff event. It is given by:

$$WP = \left(\frac{ZZ}{MPT}\right)^{EX1}, \text{ but not greater than unity.} \qquad (4.9)$$

ZZ is the ordinate number corresponding to the latest observed discharge; that is, NOB + PJ.

MPT is the ordinate number corresponding to the peak of the hydrograph. Conceptually, this is the peak of the observed hydrograph, but, in the computations, it is based on the simulation. The reason is that prior to the peak ($ZZ<MPT$), it has not been observed. Subsequent to the peak ($ZZ>MPT$), the two are essentially the same. The simulated hydrograph from which MPT is determined is that which was obtained by applying adjustments at earlier time periods but before any adjustments are made at the time in question.

In a case where the runoff event begins on the recession of a previous event, it is possible for the latest simulated ordinate to be smaller than the first ordinate on the observed/simulated hydrograph. Obviously, the first ordinate, while largest in the array, should not be considered the peak for purposes of computing MPT. To prevent it from being used this way, at each time period the time of the center of mass of the observed precipitation is determined and the value of MPT is constrained to a value no less than this.

EX1 is an exponent which permits the variation of WP with time to be made nonlinear. A value of 2 has been used in the investigation.

It should be noted here that the quantity, WP, or some other function related to the development of the event, could have been applied to the objective function rather than to the tolerance. That is, decreasing the objective function early in the rise or increasing the tolerance would accomplish the same thing.

Another point, which has been noted earlier, is that the computation of the objective function and the tolerance, or the execution of CHAT itself, after the peak has passed is obviously unnecessary for purposes of forecasting the peak. The reason for continuing to make adjustments until the end of the event is to have the final adjusted values of the soil moisture accounting state variables be influenced by all of the observed discharge data. This is accomplished by fitting the entire hydrograph to observed data rather than just the rising limb.

Figure 4.1 illustrates the variation of the tolerance with time and with discharge for a typically shaped hydrograph. Note that at the beginning of the rise the tolerance is quite large. Up until approximately the time of ordinate no. 3, the tolerance is so large compared to the discharge values involved that it is very easily satisfied and it is not likely that any adjustments would be made. And none should be made on the basis of such a small part of the observed hydrograph. As the rise develops, the tolerance follows a generally downward trend in actual value and becomes much smaller in relation to the magnitude of the discharge being experienced. Finally, at ordinate no. 6, when the peak and 37 percent of the runoff have been observed, it is quite restrictive. Following the peak, the tolerance drops off rather rapidly as each increment of time produces a large increase in the percentage of runoff that has been observed and, consequently, a large improvement in the reliability of the adjustment procedure. At the time of ordinate no. 9, the average observed discharge attains a value equal to the current discharge. From that point on, PCOB is based on the average discharge and the tolerance decreases much more slowly. This prevents it from dropping off to very small values which would be virtually impossible to satisfy.

Unit Hydrograph Adjustment

As has been explained, the purpose of the unit hydrograph adjustment algorithm is to convert the unit hydrograph representing average runoff conditions to one that reflects the runoff distribution exhibited by the specific event that is being simulated. Such a hydrograph is assumed to be generally similar in shape to the average graph but to differ somewhat in sharpness and in timing. This is to be accomplished under the control of a numerical optimization strategy. That is, the altered hydrograph must be related to the original by a series of numerical values that are manipulated by the program in a manner similar to the manipulation performed on the precipitation input data.

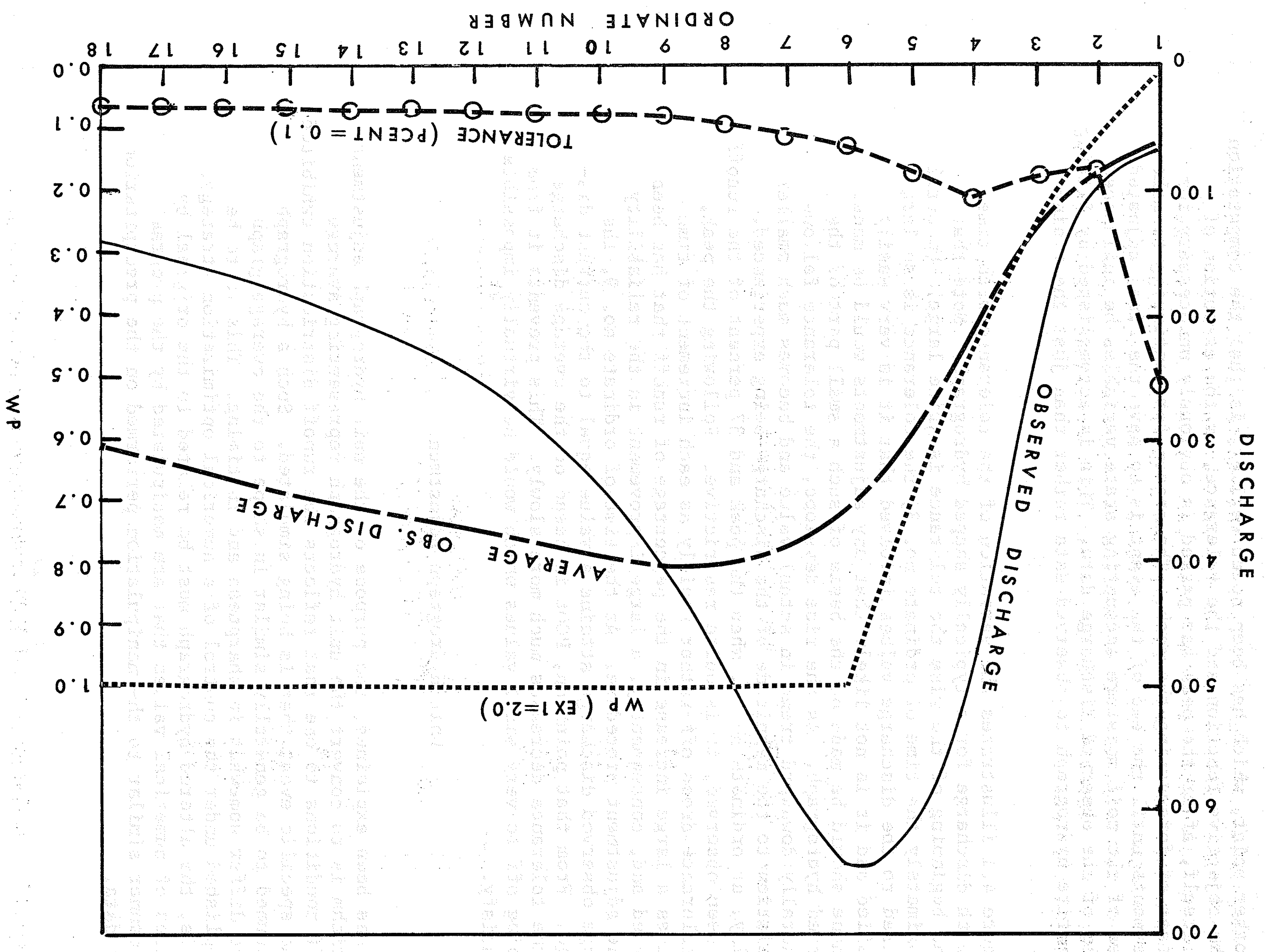


Figure 4.1--Variation of tolerance with discharge and with time

The algorithm that performs this transformation is the "unit hydrograph warping" algorithm and is expressed by Subroutine WARP. The manner in which the alteration takes place is defined by two "warp coefficients," RH and RV. That is, the input to Subroutine WARP is the original unit hydrograph, defined by its ordinates, and the two warp coefficients. The output is the adjusted, or warped, unit hydrograph. Figure 4.2 illustrates how this portion of the adjustment technique operates.

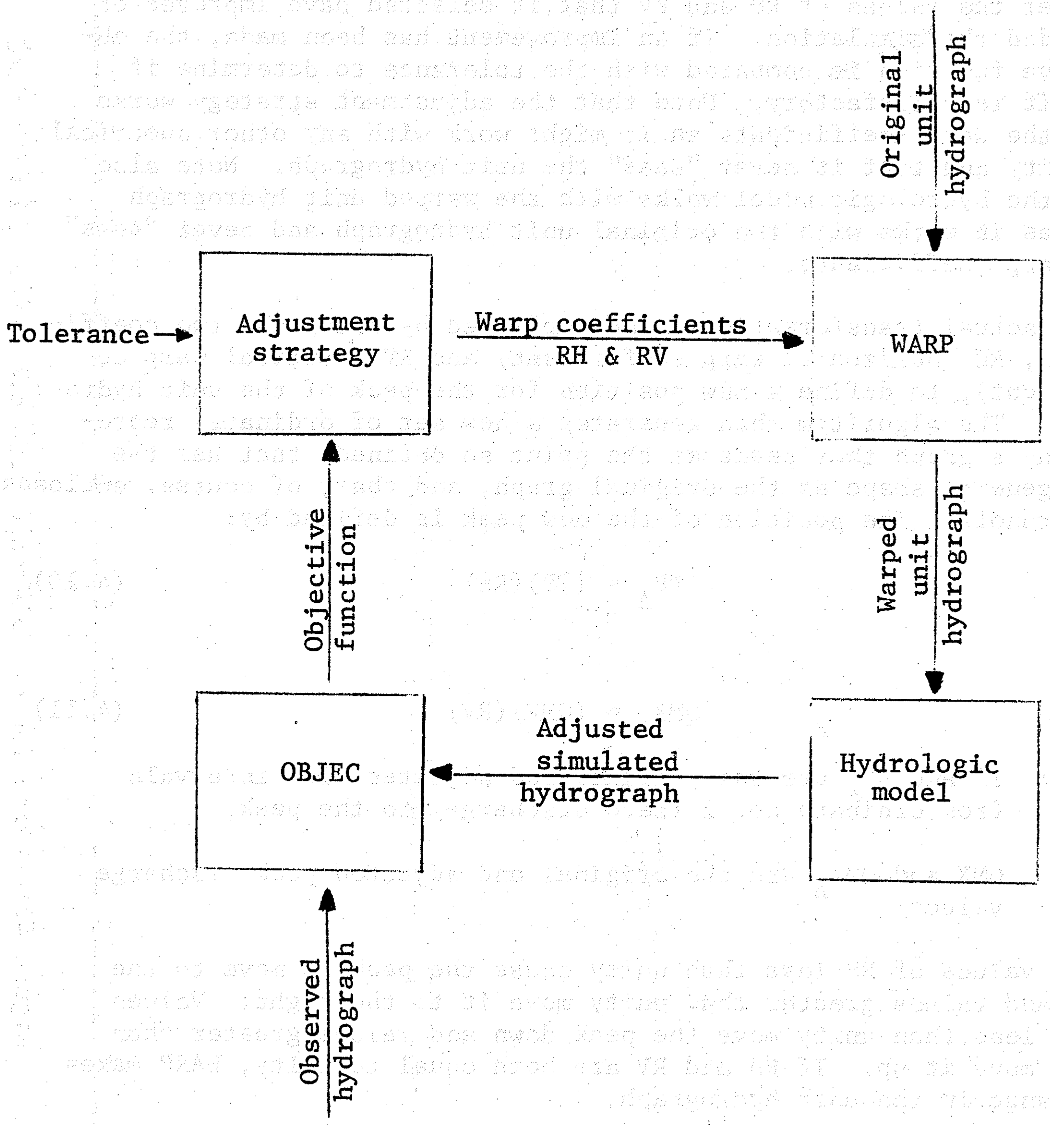


Figure 4.2. - Relationship of WARP subroutine to other components.

The adjustment strategy selects values of the warp coefficients, RH and RV, and passes them to the WARP subroutine. Using these coefficients, WARP operates on the original unit hydrograph to produce a warped unit hydrograph, which it passes to the hydrologic model. The model produces an adjusted simulated hydrograph which reflects the changes made in the unit hydrograph on the basis of the warp coefficients. The simulation is compared with the observed hydrograph by Subroutine OBJEC, which computes the objective function. The adjustment strategy then examines the objective function to determine whether the values of RH and RV that it selected have improved or degraded the simulation. If an improvement has been made, the objective function is compared with the tolerance to determine if the fit is satisfactory. Note that the adjustment strategy works with the warp coefficients as it might work with any other numerical quantity and that it never "sees" the unit hydrograph. Note also that the hydrologic model works with the warped unit hydrograph just as it works with the original unit hydrograph and never "sees" the warp coefficients.

The actual transformation is accomplished by using the two coefficients, RH (horizontal warp coefficient) and RV (vertical warp coefficient), to define a new position for the peak of the unit hydrograph. The algorithm then generates a new set of ordinates representing a graph that peaks at the point so defined, that has the same general shape as the original graph, and that, of course, encloses unit runoff. The position of the new peak is defined by:

$$TP_A = (TP)(RH) \tag{4.10}$$

and

$$QMX_A = (QMX)(RV) \tag{4.11}$$

where: TP and TP_A are the original and adjusted time intervals from ordinate no. 1 (zero discharge) to the peak,

QMX and QMX_A are the original and adjusted peak discharge values.

Thus, values of RH less than unity cause the peak to move to the left and values greater than unity move it to the right. Values of RV less than unity move the peak down and values greater than unity move it up. If RH and RV are both equal to unity, WARP makes no change in the unit hydrograph.

The horizontal portion of the warping procedure is accomplished by simply translating the hydrograph right or left far enough to move the peak to the time defined by RH. After the translation, the first and last ordinates are set to zero. In some cases, this results in a small amount of volume being lost. As will be shown later, however, this is automatically restored by the vertical portion of the procedure.

The vertical portion of the warping procedure is accomplished by adjusting each of the ordinates with the following equation:

$$Q_A = Q * RV \left(\frac{1+A(1-CRV)}{RV}\right)^B \tag{4.12}$$

where: Q and Q_A are the original and adjusted values of the ordinate and A and B are coefficients. CRV is the curvature of the hydrograph at the ordinate in question. It is given by:

$$CRV = \frac{Q(N)}{[Q(N-1) + Q(N+1)]/2} \tag{4.13}$$

That is, CRV is greater than unity where the graph is concave downward, less than unity where concave upward, and equal to unity at inflection points. CRV is normally less than unity for the lower portions of the rise and recession and greater than unity just before, at, and just after the peak.

Given a unit hydrograph defined by a series of ordinates, Q, Eq. (4.12) will generate a family of adjusted hydrographs, each set of values of A and B defining a different graph. The definition of the vertical warp coefficient, RV, however, requires (Eq. (4.11)) that the adjusted <u>peak</u> discharge be equal to the product of RV and the original <u>peak</u> discharge. Applying Eq. (4.12) to the peak and letting CMX represent the curvature at the peak, Eq. (4.12) becomes:

$$Q*RV = Q*RV \left(\frac{1+A(1-CMX)}{RV}\right)^B \tag{4.14}$$

or

$$\left(\frac{1+A(1-CMX)}{RV}\right)^B = 1 \,. \tag{4.15}$$

For any value of the exponent B, other than zero, the expression [1+A(1-CMX)]/RV must be equal to unity. Solving for coefficient A then gives:

$$A = \frac{RV - 1}{1 - CMX} . \tag{4.16}$$

Thus, there is only one value of A that will produce the required peak adjustment and it is given by Eq. (4.16). Since the unit hydrograph must always be concave downward at the peak, CMX must be greater than unity. Therefore, the sign of coefficient A depends on whether the vertical warp coefficient is greater or less than unity. That is:

$$\text{If} \quad RV > 1, \quad A < 0$$

$$\text{If} \quad RV < 1, \quad A > 0 .$$

Looking again at Eq. (4.12), if the value of exponent B is 1.0, the equation becomes:

$$Q_A = Q[1+A(1-CRV)] . \tag{4.17}$$

Then, for a warp coefficient greater than unity, which increases the peak, RV > 1, A < 0, and:

$$\text{If} \quad CRV < 1, \quad Q_A < Q$$

$$\text{If} \quad CRV = 1, \quad Q_A = Q$$

$$\text{If} \quad CRV > 1, \quad Q_A > Q .$$

Conversely, with a warp coefficient less than unity, which decreases the peak, RV < 1, A > 0, and:

$$\text{If} \quad CRV < 1, \quad Q_A > Q$$

$$\text{If} \quad CRV = 1, \quad Q_A = Q$$

$$\text{If} \quad CRV > 1, \quad Q_A < Q .$$

This demonstrates the properties of Eq. (4.12). If RV is greater than unity, the peak and all ordinates above the inflection points are increased. All ordinates below the inflection points are decreased. If RV is less than unity, the reverse is true. In either case, if the increase exactly balances the decrease, unit volume is maintained.

If the exponent B is not equal to 1.0, then the effect will be similar but the transition will occur somewhat above or below the inflection points. Applying Eq. (4.12) then with various values of exponent B and with coefficient A defined by Eq. (4.16) will produce a family of hydrographs all of which pass through the newly defined peak but only one of which will enclose unit volume. The value of the exponent that will accomplish this is determined by iteration. If a unit hydrograph is warped horizontally and loses volume in the process as explained earlier, that volume is restored during the vertical warp by selecting a value of B that causes the volume to match that of the original unit hydrograph prior to the horizontal translation.

The mathematical characteristics of the WARP algorithm require a rather fine time discrimination in the ordinates defining the unit hydrograph. The catchment model used with CHAT utilizes a 6-hour duration unit hydrograph defined by ordinates spaced 6 hours apart. WARP requires that the ordinate spacing be 2 hours. The subroutine is dimensioned for a time base of 210 hours. That is, the unit hydrograph used as input to WARP is defined by 106 ordinates, UGI(K), covering the time base from 0 to 210 hours. The average unit hydrograph for the catchment must be defined in this way in the input to any forecast program using CHAT. Note that UGI is actually dimensioned for 107 ordinates. UGI(107), however, does not appear outside the subroutine. The final operation in the subroutine is the computation of the adjusted ordinates, which then appear in array UG. This array is also dimensioned for 107 ordinates because it is used internally with the 2-hour ordinates. At the end of the subroutine, however, it contains 36 ordinates spaced 6 hours apart and covering the 0 to 210-hour time base. This presents the unit hydrograph in the form used by the catchment model.

The values of the curvature, CRV, are actually computed in the subroutine in a somewhat different manner than described above. If the values of CRV as computed with Eq. (4.13) were used in Eq. (4.12), the results could be erratic. This is because the computation is very sensitive to the value of CRV where it is close to unity and roundoff errors in the input ordinates can produce erratic values. The alternate method consists of determining the curvature at each ordinate, using Eq. (4.12), and from these values locating all inflection points. The mean inflection point discharge is then computed, but the computation involves only those points at which the discharge is greater than 20 percent of the maximum discharge. Finally, the curvature at each ordinate is computed as the ratio of the discharge to the mean inflection point discharge. These values have properties similar to the true curvature but result in a smooth adjusted hydrograph. Figures 4.3-4.8 show the effect of operating on the same unit hydrograph with various combinations of RV and RH and demonstrate the characteristics of the algorithm. Figure 4.3 shows the application of RV slightly greater and slightly less than unity. Note that when the peak increases, the lower portions of the graph decrease and that unit volume is always maintained. In Figure 4.4, an extreme value of RV (2.0) is applied. Note that the volume is maintained by pulling in the sides and shortening the base. Figure 4.5 shows the effect of a numerically small vertical warp coefficient, 0.7. Note that the peak has become very flat. In fact, in order to maintain volume, the algorithm has generated ordinates to the left and right of the "peak" that are slightly higher than the "peak." This illustrates the need for constraints on the values of the warp coefficients to be used with this algorithm. For this particular unit hydrograph, a lower constraint on RV of slightly over 0.7 would be appropriate and this is fairly typical. Figure 4.4 demonstrates that the upper constraint on RV may be much less restrictive.

Figure 4.6 shows the effect of RH values greater and less than unity, which produce pure translation. Note that where RH = 0.7, a small amount of volume (5 percent) has been lost. This case, RH < 1 and RV = 1, is the only situation in which the algorithm may not maintain unit volume. This is not particularly important since the usual situation involves values other than unity for both coefficients. Where RV $\neq$ 1, the vertical warp operation restores the volume lost during a horizontal shift to the left. As will be noted later, the optimization strategy always operates first on RV and then on RH. So, while a situation of this type can occur, the chance of it is minimal. In Figure 4.7, application of RH = 0.8 reduces the volume but the vertical warp with RV = 1.1 restores it, and the area under both hydrographs shown is the same. Had the vertical warp coefficient been less than unity, the peak would have been reduced in magnitude, but the lost volume would still have been restored. Figure 4.8 illustrates the effect of RV < 1 and RH > 1.

The previous examples show that the mathematical characteristics of the warp subroutine impose the need for lower constraints of about 0.7 on both warp coefficients, but they impose no such requirement with respect to upper constraints. As will be pointed out in the section on optimization strategy, constraints are imposed on all of the decision variables with which CHAT is involved, and these constraints are related to the physical system being treated. Experience has shown that the physical constraints on the warp coefficients are at least as restrictive as those just noted, thereby rendering the mathematical constraints redundant.

It was stated above that the value of the exponent B, which will cause the volume of the warped unit hydrograph to equal that of the original, is determined by iteration. In this procedure, the volumes corresponding to three different values of B are determined, and

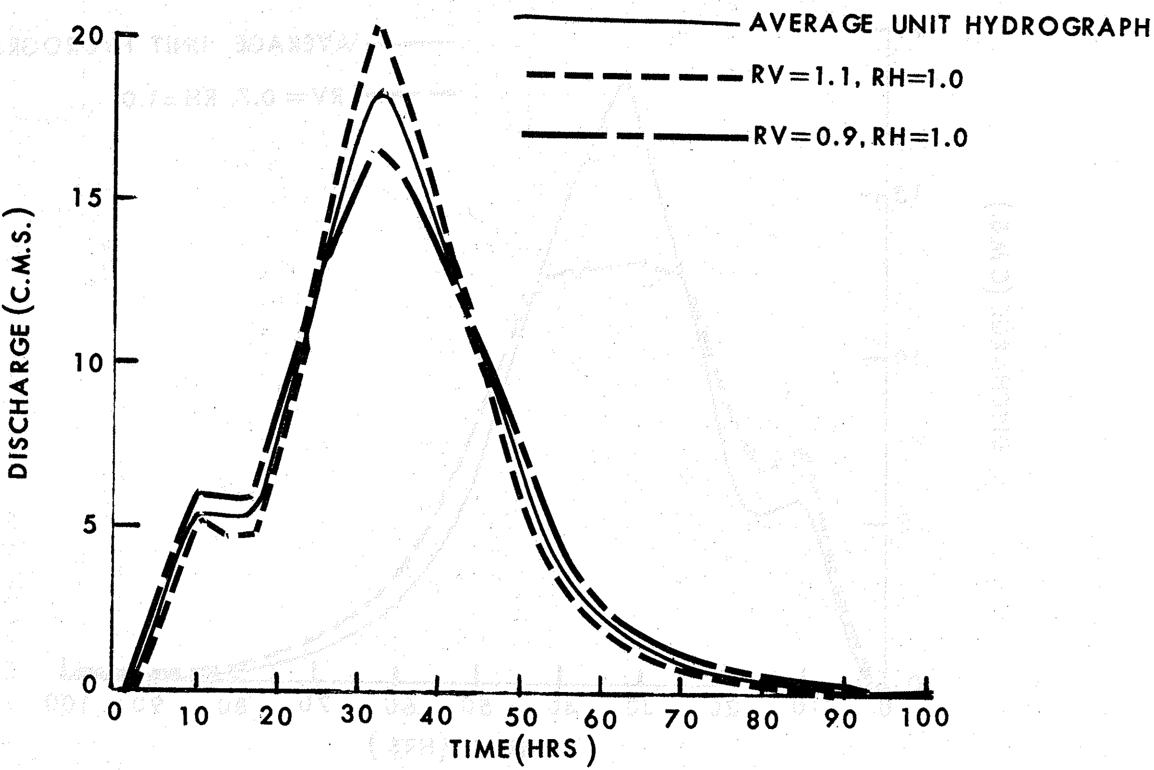


Figure 4.3--Effect on unit graph of varying vertical warp coefficient--RV=1.1, RV=0.9

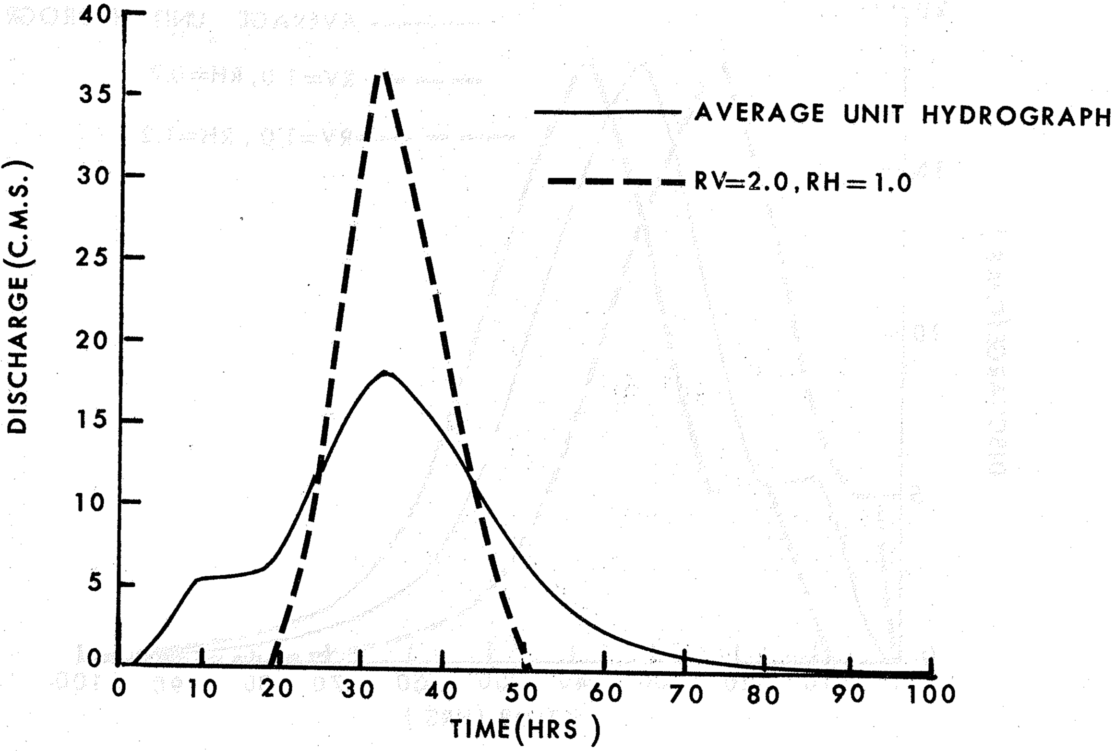


Figure 4.4--Effect on unit graph of numerically large vertical warp coefficient--RV=2.0

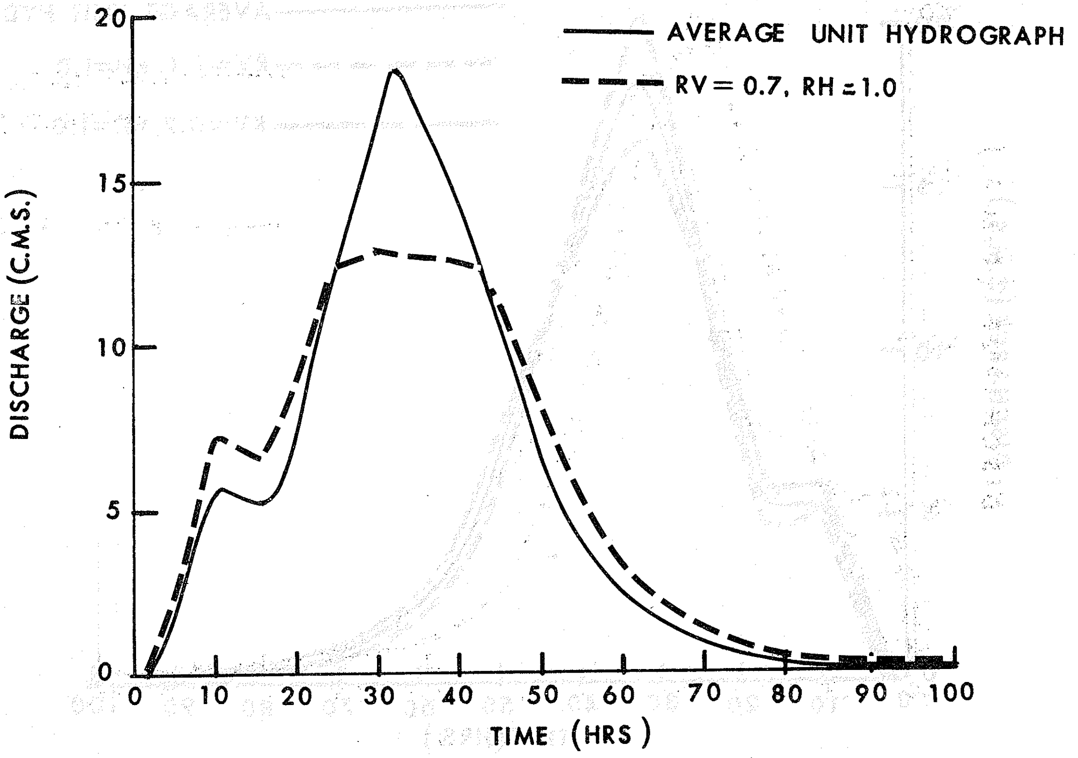


Figure 4.5--Effect on unit graph of numerically small vertical warp coefficient--RV=0.7

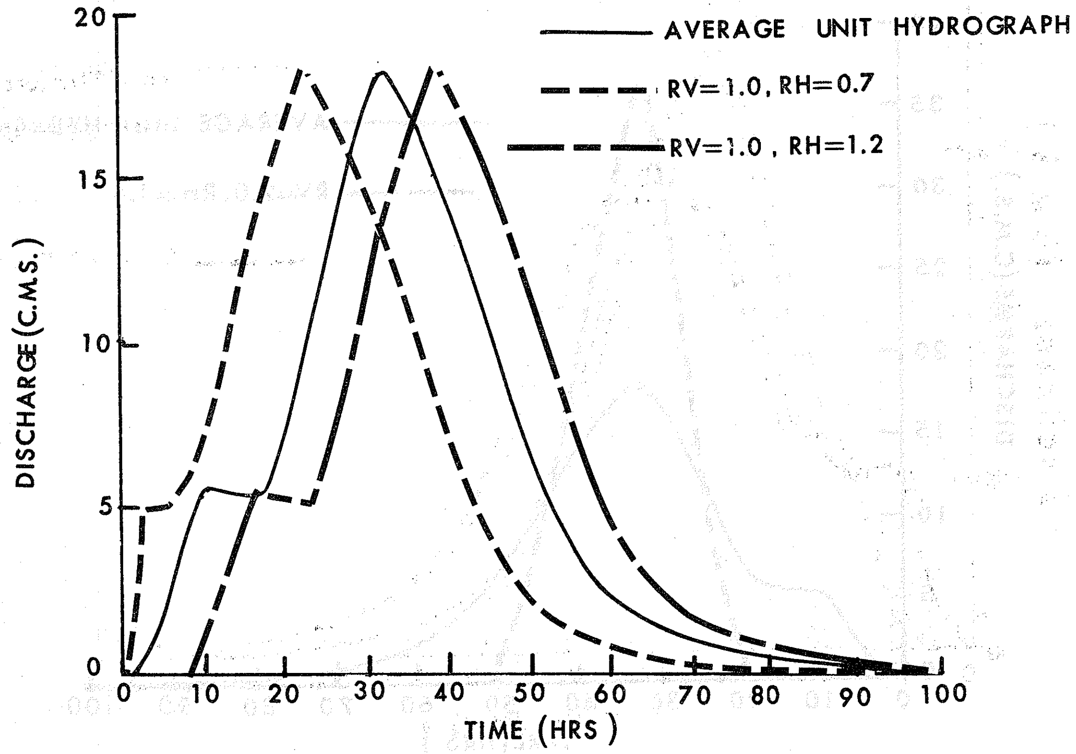


Figure 4.6--Effect on unit graph of varying horizontal warp coefficient--RH=0.7, RH=1.2

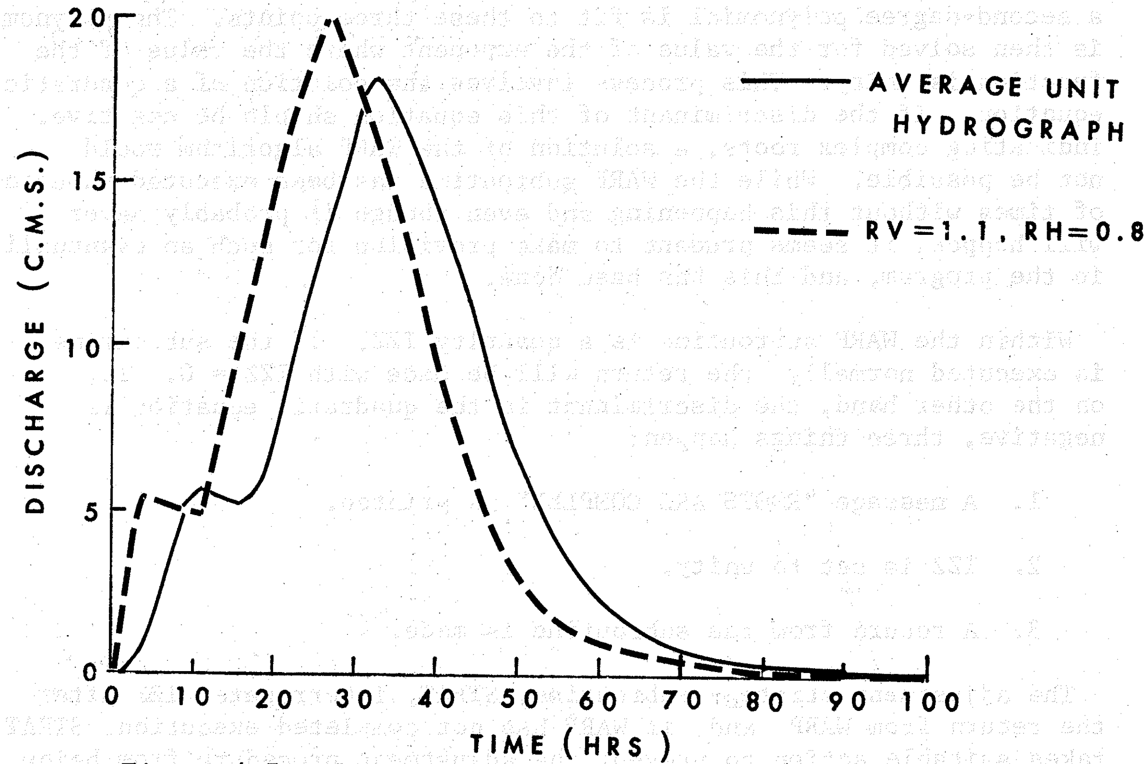


Figure 4.7--Effect on unit graph of varying both coefficients simultaneously--RV=1.1, RH=0.8

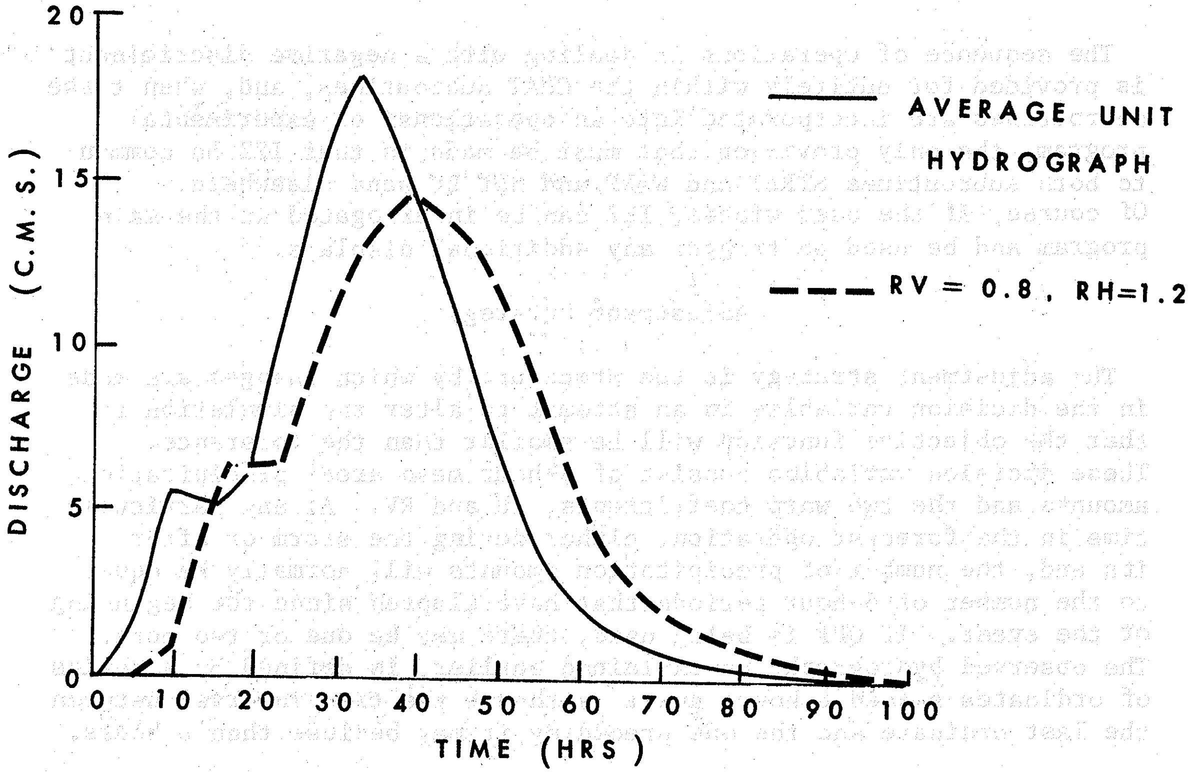


Figure 4.8--Effect on unit graph of varying both coefficients simultaneous--RV=0.8, RH=1.2

a second-degree polynomial is fit to these three points. The polynomial is then solved for the value of the exponent where the value of the function is unity. This process involves the solution of a quadratic equation. If the discriminant of this equation should be negative, indicating complex roots, a solution of the WARP algorithm would not be possible. While the WARP subroutine has been executed thousands of times without this happening and even though it probably never will happen, it seems prudent to make provision for such an eventuality in the program, and this has been done.

Within the WARP subroutine is a quantity IZZ. If the subroutine is executed normally the return will be made with IZZ = 0. If, on the other hand, the discriminant in the quadratic equation is negative, three things happen:

1. A message "ROOTS ARE COMPLEX" is printed.

2. IZZ is set to unity.

3. A return from the subroutine is made.

The adjustment strategy subroutine, STRAT, interrogates IZZ after the return from WARP, and, if WARP has not completed execution, STRAT takes suitable action to prevent the adjustment procedure from being aborted. The manner in which this is done is described in the next section.

The sequence of operations in dealing with a negative discriminant is provided for entirely within the CHAT subroutines, and, when these subroutines are incorporated into an operational or experimental program, the only provision that must be made is that IZZ be common to both subroutines STRAT and WARP and not be used elsewhere. Of course, if the user wishes, IZZ can be interrogated in the main program and be used to trigger any additional displays.

Adjustment Strategy

The adjustment strategy is the procedure by which changes are made in the decision variables in an attempt to alter the simulation so that the objective function will be smaller than the tolerance. These decision variables consist of 6-hour mean areal precipitation amounts and the two warp coefficients, RH and RV. At any particular time in the forecast operation, either during the storm or after its end, the number of precipitation amounts will normally be equal to the number of 6-hour periods that have elapsed since the beginning of the event. If QPF is being used, there may be one or two more. The observed hydrograph, as explained earlier, is defined by a series of ordinates spaced 6 hours apart, although the time interval between the last ordinate and the one preceding it may be less than 6 hours.

If the observational reporting system is operating in the prescribed manner and if QPF is not being used, the last precipitation observation will coincide, in time, with the end of the observed hydrograph. The adjustment strategy does not, however, depend on the existence of this condition. The last available discharge observation may be at a time prior to the last precipitation observation either because the river observations are not current or because some of the precipitation is based on QPF and is in the future. Or the forecast might be prepared 2 hours after precipitation observation time and include in the observed hydrograph a river observation made just a few minutes prior to forecast preparation. In any event, the strategy works with all precipitation increments up to the latest available, including QPF, if any. The objective function is computed up to the end of the observed hydrograph. Neither the strategy nor the objective function recognizes, explicitly and directly, which of the three possible conditions exists. What in fact happens is that the strategy will not make any changes in a particular precipitation period if none of the runoff resulting from that precipitation has been "seen" at the river gage. That is, adjustments will be made only to precipitation that fell prior to the last discharge observation. The reason the strategy will not change precipitation that fell, or may fall, subsequent to the end of the observed hydrograph is not that it knows it shouldn't, but that when it attempts to do so it will find that it cannot possibly change the objective function, and it will therefore not change the precipitation. This means, among other things, that if one or more periods of QPF are included in a forecast, it is not necessary to tell CHAT that this is forecast rainfall. CHAT will make no changes in it. One possible exception to this is the case where a river observation is made a few hours after the last precipitation observation and QPF is being used in that 6-hour period. Then, a change in the precipitation for that period can affect the objective function and such change may be made.

The adjustment process consists of making a number of "passes" through the strategy. In each pass, a maximum of three changes can be made. One 6-hour precipitation amount and only one can be increased or decreased by an amount, Δ, probably 1 mm. Either or both of the warp coefficients can be increased or decreased by an amount, ΔW, probably 0.01. At the completion of a pass, if an exit condition has been reached, the adjustment process is terminated. If not, another pass is made.

As stated, within a pass, only one precipitation amount can be changed and that is the one that produces the greatest improvement in the objective function. Furthermore, at the time this change is made, in the first pass, a sensitivity term, STY, is computed. STY is equal to 7.5 percent of the ratio of the improvement in the objective function to the function itself. The value of the objective function at this time is designated as OFBSE. On subsequent passes, no change will be made unless the ratio of the change to OFBSE exceeds STY.

The rationale behind this type of strategy is similar to that behind the quantity, WP, which is one of the components of the tolerance. It was pointed out, in the section dealing with the tolerance, that during the early part of the rise, when only a small portion of the runoff volume has been sampled, there is little justification for making substantial changes in the decision variables. A similar factor is involved in the adjustment procedure. The adjustment strategy, however, is dealing with a series of 6-hour precipitation increments. The simulated hydrograph, as well as the observed, is a composite of a series of contributions each one of which is in a different stage of development. Just as large changes in the simulation cannot be justified on the basis of what is seen early in the rise, changes in an individual 6-hour precipitation amount cannot be justified when only a small part of the contribution of <u>that</u> 6-hour amount has been seen. As an example, suppose that at one point in time during a forecast operation, there are three precipitation periods involved. Depending on a number of factors, primarily the characteristics of the catchment, perhaps only a tiny portion of the runoff resulting from period 3 has appeared at the gage. The rate of runoff resulting from period 2 precipitation is at a maximum, however, and the contribution of period 1 has already peaked and is in recession. Under these circumstances, the desired strategy would be to work primarily with period 2. Period 3 should be adjusted slightly if at all because its contribution has not yet been seen. Any necessary adjustments to period 3 <u>will be</u> made at a subsequent time. Period 1 need not be adjusted substantially because it <u>was</u> adjusted at some previous time when it, rather than period 2, was the most critical. It should be noted at this point that adjustments to period 1 or 3 will not affect the objective function as much as will changes in period 2. Period 1 will have a slight effect because the portion of the simulation it affects the most is some period back from the current time and weight, WD, in the objective function reduces the effect of errors in that portion of the simulation. Period 3 will have a slight effect because the portion of the simulation it affects the most is in the future and is not included in the objective function at all. The reason for restricting adjustments to those precipitation periods that are affecting the hydrograph the most at the time the adjustment is being made is to avoid making unrealistic and unjustified changes in recent precipitation periods simply because they produce an improvement in the fifth decimal place of the objective function. Such adjustments can make substantial and unjustified changes in the future portion of the simulation. While such changes would presumably be rectified at a later time, they would work to the detriment of the forecast issued at the time in question. Once again, the aim is not to minimize the objective function subject to constraints on the decision variables but rather to reduce the objective function to an acceptable value while making minimal changes in the decision variables. This dictates a basically different strategy than would be appropriate for a classic optimization procedure.

To accomplish this strategy requires a determination of the relative importance to the objective function of the various precipitation periods at the time the forecast is being made. It would be possible to compute this information as a function of the model's parameters and state variables, but the complexity of such an analysis would approach that of the model itself. Therefore, the actual simulations are used for this purpose. Within each pass, increments or decrements are applied to each precipitation period and the change in the objective function noted. Then, all are reset to their starting values except the one which produced the maximum change. On subsequent passes, further changes would probably be made in that period until it nears its optimal value and then some other period may become the most critical. The procedure continues until the maximum change that can be produced is less than the sensitivity figure, STY, or until the tolerance is reached or until some other exit condition is met.

The adjustment of the unit hydrograph is done in a different manner. Adjustments are made to either RV, RH, or both if such adjustment will improve the fit. Since the same adjusted unit hydrograph is applied to the runoff from all precipitation periods, all necessary controls are exercised by the objective function and the tolerance.

The simplified flow chart in Figures 4.9(a) and 4.9(b) illustrates the adjustment process. When the process begins, at the box marked "START," the following conditions exist.

A. The number of 6-hour periods that have elapsed since the beginning of the runoff event is denoted by "N." N may be any value from 1 up to that which represents the entire hydrograph base.

B. Six-hour mean areal precipitation amounts have been computed from rain gage observations, radar, etc., for periods 1 through N, and some of these amounts may be zero.

C. Nonzero precipitation amounts for periods N+1, N+2, etc., may be involved in the simulation, but if so, they are QPF.

D. Discharge observations are available up to some point in time no later than a couple of hours after the end of period N. All computations of the objective function and tolerance will be based on the hydrographs up to this time.

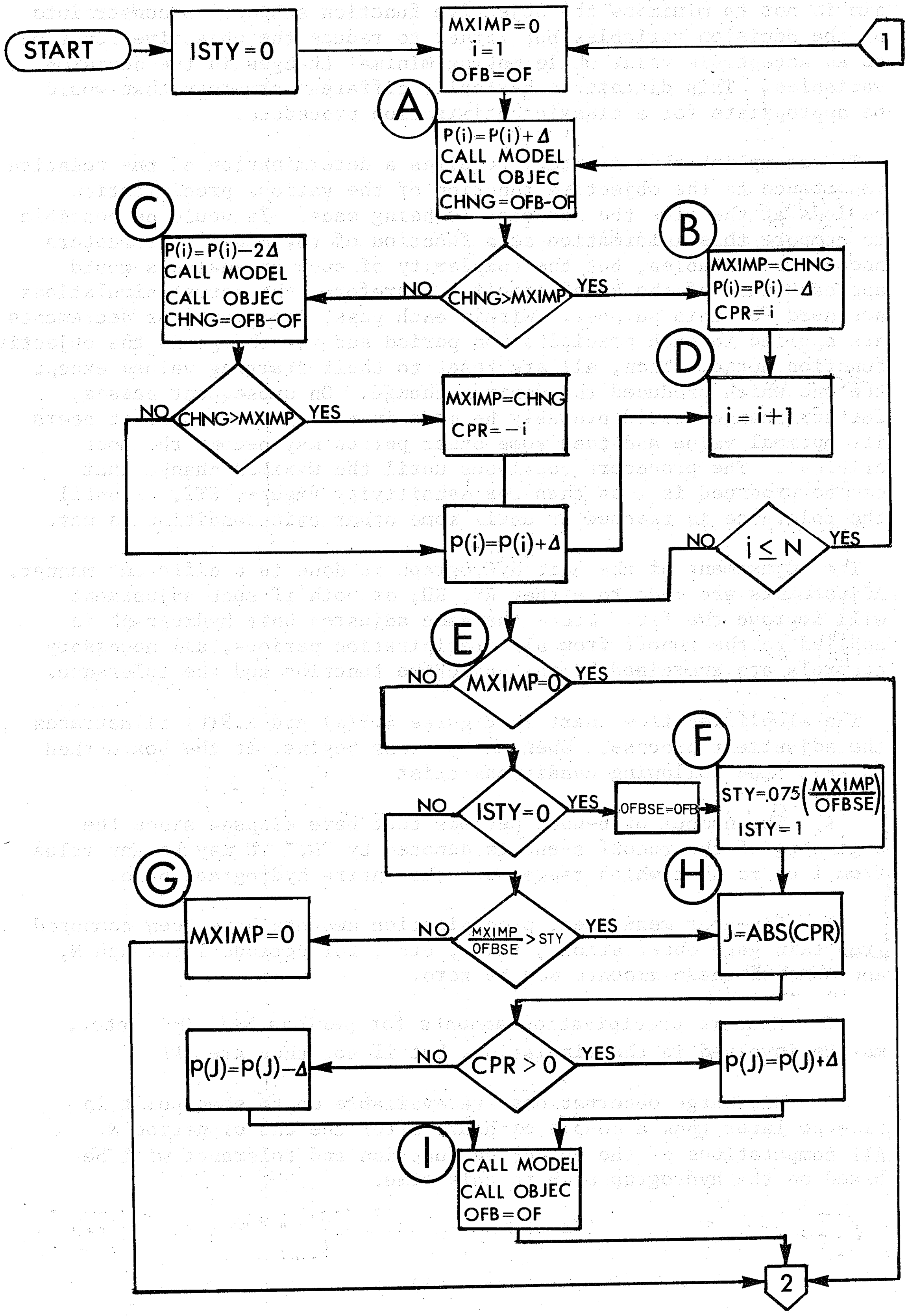


Figure 4.9a--Adjustment strategy (precipitation)

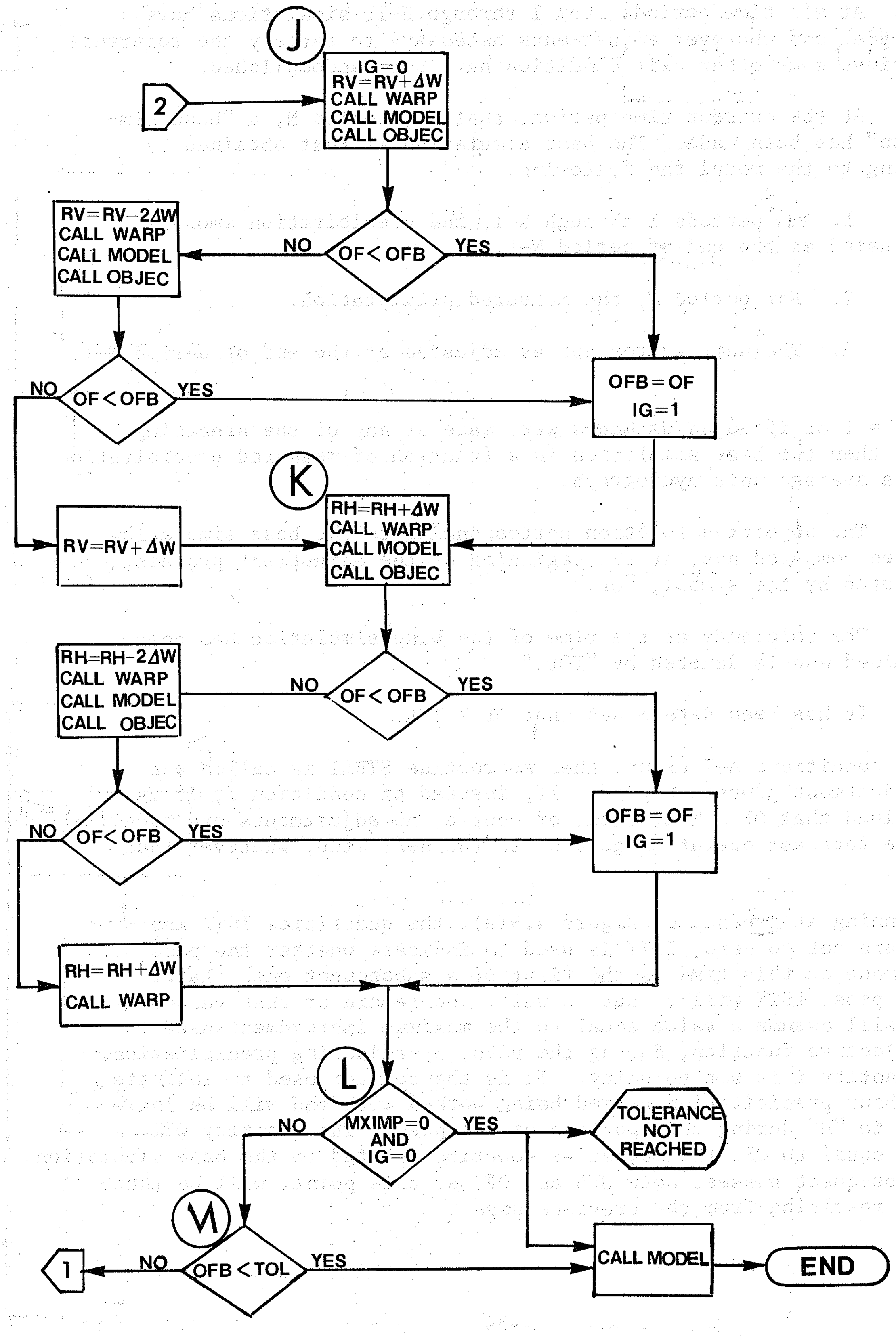


Figure 4.9b--Adjustment strategy (unit hydrograph)

E. At all time periods from 1 through N-1, simulations have been made, and whatever adjustments necessary to satisfy the tolerance or achieve some other exit condition have been accomplished.

F. At the current time period, that is, period N, a "base simulation" has been made. The base simulation is that obtained by applying to the model the following:

1. For periods 1 through N-1, the precipitation amounts as adjusted at the end of period N-1.

2. For period N, the measured preciptation.

3. The unit hydrograph as adjusted at the end of period N-1.

If N = 1 or if no adjustments were made at any of the preceding times, then the base simulation is a function of measured precipitation and the average unit hydrograph.

G. The objective function corresponding to the base simulation has been computed and, at the beginning of the adjustment process, is denoted by the symbol, "OF."

H. The tolerance at the time of the base simulation has been determined and is denoted by "TOL."

I. It has been determined that OF > TOL.

When conditions A-I exist, then subroutine STRAT is called and the adjustment process begins. If, instead of condition I, it is determined that OF < TOL, then, of course, no adjustments are made, and the forecast operation goes on to the next step, whatever that may be.

Beginning at the top of Figure 4.9(a), the quantities ISTY and MXIMP are set to zero, ISTY is used to indicate whether the pass being made at this time is the first or a subsequent one. Later in the pass, ISTY will be set to unity and remain at that value. MXIMP will assume a value equal to the maximum improvement made to the objective function, during the pass, by adjusting precipitation. The quantity i is set to unity. It is the counter used to indicate the 6-hour precipitation period being worked with and will be incremented to "N" during this portion of the pass. The quantity OFB is set equal to OF, the objective function related to the base simulation. For subsequent passes, both OFB and OF, at this point, will be those values resulting from the previous pass.

With the initialization of the pass completed, adjustment of the precipitation begins at point "A." P(i) is incremented by Δ, and a simulation is made by calling subroutine MODEL. This subroutine is not one of the component parts of CHAT. Rather it is the means by which CHAT is linked to any research or operational program that uses CHAT. The function of subroutine MODEL is simply to call whatever mainline program subroutines are needed to produce a simulation and place the ordinates in the array utilized by subroutine OBJEC. Next, the objective function is computed and the quantity CHNG, which is the change in the objective function resulting from incrementing P(i). If the fit has been improved, CHNG will be positive; if it has been degraded, CHNG will be negative.

Next, CHNG is compared with MXIMP. If $i = 1$, MXIMP will be zero. If $i > 1$, MXIMP will probably be other than zero. It cannot be negative. If CHNG > MXIMP, then the incrementing of P(i) has produced an improvement in the fit, and it is the greatest improvement so far this pass. If this condition exists, the statements in box "B" set MXIMP equal to CHNG, reset P(i) to its previous value and set the quantity "CPR" equal to i to "remember" which precipitation value produced MXIMP. If, on the other hand, CHNG is not greater than MXIMP, the program proceeds to point "C," where a similar procedure takes place but with P(i) being <u>decremented</u> by Δ. If this produces a change greater than MXIMP, a similar substitution is made, but now, CPR is set to "-i," indicating a decrementing of the precipitation rather than incrementing. In any event, P(i) is reset to its previous value and the program proceeds to point "D," where "i" is incremented. If $i \leq N$, a return is made to point "A."

After all precipitation periods have been tested, the program proceeds to point "E." At this point, all precipitation values have been reset to the values they had at the beginning of the pass, MXIMP shows the greatest improvement achieved, and CPR shows how it was accomplished.

Next, MXIMP is tested against zero. If zero, it means that no changes in precipitation have been made during the pass. In that event, the program branches, via point "2," to the unit hydrograph portion of the strategy. If MXIMP ≠ 0, it is then necessary to test the improvement against the sensitivity, STY, as described earlier. Or, if this is the first pass, (ISTY=0), STY is computed in box "F," and ISTY is set to unity. Once STY is computed, it is not changed. If it is not the first pass and if the ratio of MXIMP to OFBSE is less than STY, MXIMP is set to zero at point "G," and the program proceeds to point "2" without adjusting precipitation. If an adjustment is to be made, however, the path is through point "H." The precipitation period that is associated with MXIMP is either incremented or decremented, as indicated by the sign of CPR. Then, the statements in box "I" create a new simulation and its corresponding objective function, OF. At this point, OFB is set equal to this value of OF and the program proceeds to the unit hydrograph adjustment in the portion of the chart shown in Figure 4.9(b).

This adjustment starts at point "J" by applying an increment, ΔW, to the vertical warp coefficient, RV, and producing a simulation. If this simulation improves the fit, indicated by the new objective function, OF, being less than the previous value, OFB, then this adjustment is retained, regardless of the size of the improvement, and OFB is set equal to OF and the quantity, IG, which had been set to zero in box "J," is set to unity to indicate that an adjustment to the unit hydrograph has been made. If incrementing RV does not produce an improvement, it is decreased by 2ΔW, to its original value minus ΔW, and a similar test is made. If no improvement can be made, RV is set to its original value.

Whether or not a change is made in RV, the program proceeds to point "K," where a similar procedure takes place involving the horizontal warp coefficient, RH. At the completion of this procedure, a test is made, at point "L," to determine if both MXIMP and IG are equal to zero. If they are, it means that no adjustments were made during the pass. It also means that additional passes would achieve the same result. Consequently, an exit condition has been reached. This exit condition requires that some message or other indication show that the adjustment procedure was terminated without reaching the tolerance.

If either MXIMP or IG is other than zero, one or more changes has been made during the pass. In this case, a test is made, at point "M," to determine if the tolerance has been reached. If it has, the normal exit occurs. If it has not, the routine branches back to point "1" to begin another pass. When an exit takes place, all decision variables have been set to their adjusted values, the simulation existing at that time corresponds to those values, and the objective function corresponding to that simulation is that represented by symbol OFB and also OF.

It should be noted at this point that if, in a pass, it is not possible to improve the fit by adjusting precipitation but changes to the unit hydrograph are made in that pass, it does not follow that no changes to precipitation will be made in subsequent passes. It is quite possible that the change in simulation that results from warping the unit hydrograph will make it possible to improve the fit by adjusting precipitation in later passes.

The flow chart is, as was noted earlier, a simplification. The subroutine has provision for an additional exit condition, not shown on the chart. The maximum allowable number of passes, MAXN, is specified by the user, and, if this number is made, the adjustment procedure will terminate even if no other exit condition exists.

Also, not shown on the chart is the use of constraints on the decision variables. If the various parameters used by CHAT are properly defined and if the input data contain no gross errors in observation or transmission, CHAT should operate quite nicely unconstrained. Since these conditions cannot be assumed to exist at all times, however, it is prudent to constrain the variables. In the great majority of cases, the constraints are not reached. Their main function is to prevent gross data errors such as mis-punching or misplaced decimal points from creating ridiculous results. Appropriate constraints on the warp coefficients depend upon the shape of the unit hydrograph and the characteristics of the catchment with regard to typical storm movement and areal variation of precipitation. Values of 0.7 and 1.5, however, for lower and upper constrains on both warp coefficients are reasonable and should be adequate in the majority of applications.

For precipitation adjustments, the lower constraint is simply a multiple of the measured 6-hour value. The upper constraint can take either of two forms, a multiple of the measured 6-hour value or a fixed amount. The choice between the two forms is, in effect, a user option. Actually, the parameters defining both forms are specified in all cases. The values of these parameters cause the program to select the form of constraint desired by the user.

That is, if it is felt that the precipitation computed from rain gages must always bear some relationship to the true areal mean, the user specifies an upper constraint ratio such that the constraint is equal to the product of the ratio and the measured areal precipitation. Under some climatic regimes, however, it is possible to experience a rainfall amount so large as to be totally unrelated to the mean computed from rain gage readings. In these circumstances, it is more appropriate to simply constrain the MAP to a "non-preposterous" value by the use of a fixed upper constraint which is not a function of the measured precipitation. This constraint should be a function of the region, of the size of the catchment, and of course, of duration, which is always 6 hours. If this option is to be exercised, the recommended value is 50 percent of PMP (probable maximum precipitation).

When the upper constraint is computed as a multiple of the measured precipitation, a value measured as zero will have upper and lower constraints of zero and consequently cannot be changed by the adjustment technique. Since it is quite possible for a 6-hour MAP value to be computed from rain gage observations as zero when in fact the true MAP is not zero, it is necessary to place a lower limit on the upper constraint. The value used for this limit is 20 percent of the total accumulated 6-hour precipitation up to and including the 6-hour period in question.

Thus, to define the precipitation constraints for a catchment, CHAT requires the definition of three parameters: ZLOW, the lower constraint ratio; HIGH, the upper constraint ratio; and UCX, the fixed upper constraint. The program computes the lower constraint as:

$$LK(i)=ZLOW*P(i). \qquad (4.18)$$

It computes the upper constraint as the greatest of:

$$UK(i)=HIGH*P(i) \qquad (4.19)$$

or

$$UK(i)=0.2\Sigma_1^i P(i) \qquad (4.20)$$

or

$$UK(i)=UCX(i). \qquad (4.21)$$

If the user does not wish to exercise the fixed upper constraint option, he simply specifies UCX as zero and the constraint will always be related to the measured precipitation. If a very large value of UCX is specified and if a storm occurs in which the true MAP actually exceeds UCX, if the computed precipitation is reasonably close to the true value, then the product, HIGH*P(i), will probably be greater than UCX and UCX will not constrain. Should such a storm occur and the measured precipitation be very small, CHAT may increase it up to UCX without being able to match the observed hydrograph. The program would then inform the forecaster of the circumstances and, of course, this <u>is</u> a situation in which human intervention would be desirable.

It should be noted once again that while constraints are necessary, experience indicates that their actual values are not particularly critical. In the research work already done, values of 2.0 and 0.5 have been used for HIGH and ZLOW in most cases. The adjustment procedure is capable of making substantial changes in the simulation with surprisingly small changes in the decision variables.

In the discussion of the WARP subroutine, it was pointed out that a quantity, IZZ, is set equal to unity if a return from WARP occurs without a new unit hydrograph having been generated. Subroutine STRAT interrogates IZZ after every call to WARP. If IZZ=1, STRAT does not attempt to create a new simulation and evaluate the objective function related to it. It simply bypasses these steps and does whatever it would normally do at that point if a change in RH or RV resulted in a degradation of fit.

The flow chart in Figure 4.9 and the accompanying discussion were prepared for the purpose of explaining the procedure with a maximum degree of clarity. The Fortran statements in subroutine STRAT were written to execute the procedure in a computationally efficient manner. Consequently, the symbols and the details of the operation as shown in the flow chart do not correspond exactly with those in the subroutine.

Observed Hydrograph Interpolation

The purpose of this part of CHAT, and of Subroutine INTERP, is as previously stated: to interpolate between discharge observations made at random times and produce an array of "observed" discharge values which coincide in time with the simulated ordinates. This is accomplished by fitting a segment of the hydrograph between each pair of successive observations. This segment is defined by a third-order polynomial which is fit to the observation at each end of the segment and to the slope at each end of segment. The slope is defined prior to the fitting of the polynomial and is equal to the first derivative of a <u>second</u>-order polynomial which passes through the observation in question, the one immediately preceding it, and the one immediately succeeding it. The slopes at the first and last observations are special cases and are simply the straight line slopes to the adjacent observation.

The segments combine to form a continuous smooth curve through all of the observations. Each 6-hour ordinate is determined by solving the appropriate third-order polynomial for the discharge at the time of that ordinate. The technique is similar to the method of splines, but unlike splines, will not develop unnatural oscillations.

The statements in Subroutine INTERP do not, upon cursory inspection, appear to duplicate the computational procedure described above. This is because the subroutine contains a number of mathematical "short-cuts" which greatly increase its efficiency. The results, however, are identical to those which would be obtained by following that procedure.

While this algorithm is capable of doing an excellent job of interpolating between observations, it cannot create data. The user must therefore bear in mind that the program must be supplied with enough observations to actually define the hydrograph. As noted in the subroutine documentation, the first observation must always be at time zero on the simulation scale. Since this time is prior to the beginning of rainfall, the discharge will be the "base" discharge for the event. There should be at least one observation fairly low on the rise. If there is not, the time of beginning of the rise is undefined and the interpolated hydrograph may start up too soon. It is not particularly important to have an observation exactly at the peak since INTERP will usually generate a peak between observations and higher than the highest observation. It is important to supply the program with the very latest observation available, even if it does not coincide with a 6-hour ordinate. Inclusion of such an observation not only helps to define the slope of the hydrograph at the preceding ordinate but also the observation itself will be carried over to Subroutine OBJEC as TILT and QOLT.

Blending Routine

As was pointed out in Chapter 3, the purpose of the blending routine is to effect exact agreement between two hydrographs which differ from each other by an amount which is not hydrologically significant. For this reason, the routine can be extremely simple.

Input to the subroutine consists of two discharge arrays, QO, which is the observed discharge, defined up to the latest observed ordinate, NOB, and QS, which is the simulated discharge, defined over the entire time base. The blended hydrograph appears in array QBL. From time 1 to time NOB, QBL=QO. From time (NOB+6) to the end of the simulation, QBL=QS. The five ordinates from (NOB+1) to (NOB+5) are determined by prorating, linearly, the difference between QO and QS which exists at time NOB. If a partial observed ordinate, QOLT, is available, then the difference is computed between QOLT and QS(NOB) and suitably adjusted by PJ, the fraction of the 6-hour period covered by TILT.

5. OPERATIONAL USE

The purpose of this chapter is to explain how to implement the CHAT adjustment procedure in an operational forecast program. The CHAT package is not an independent procedure but rather consists of six individual subroutines that must be interfaced with a forecast program. The CHAT subroutines perform only those operations that are associated with the function of adjusting the computed hydrograph to agree with the discharge observations. All other operations that are necessary to produce a forecast, such as I/O routines, MAP computations, rainfall-runoff computations, and runoff distribution, must be supplied by the forecast program. The manner in which the CHAT subroutines link with these other operations is described, as well as the data and parameters that the CHAT procedure requires. Subroutine listings can be found in Appendix A.

The CHAT procedure utilizes 13 parameters, each of which has been discussed in previous chapters. Provision must be made in the forecast program files for storage of these parameters. Because many of them depend upon the hydrologic characteristics of the catchment and of the gaging station and may therefore vary from one area to the next, it may be necessary to store a unique set for each headwater area. Table 5.1 lists these parameters, along with a brief description of what they are, where they are discussed in this report, and the values that have been used for them in the research work. If necessary, the research values can be used as initial values for most basins until the user acquires a better understanding of the effects they have on the performance of the procedure. At that time, however, it would be advantageous to suitably adjust them to the individual basins in order to obtain optimal performance from the procedure. Some of the experiences with parameter values that have been encountered in the research are described in Chapter 6 and may provide some useful guidelines for determining parameter values.

In addition to the parameters, CHAT requires the average basin unit graph to be defined by 2-hour instantaneous ordinates as well as by the usual 6-hour intervals, and to be placed in array UGI2(107), for use by the CHAT routines. All 107 values must be defined, even if zero, and it must begin and end with zero. It is necessary to define the unit graph in this manner for the computations inside subroutine WARP. WARP, however, returns only the 6-hour ordinates on the warped unit graph, UG6(36), so that the simulations continue to be made with a unit graph defined by 6-hour ordinates. Since adjustments to the unit graph are reflected only in array UG6(36), the average basin unit graph is always preserved in array UGI2(107).

Table 5.1. - List of CHAT parameters

Parameter	Description	Research Value	Page Reference
EX1	Exponent which permits the variation of weight WP with time to be made nonlinear in computing tolerance	2.0	16
EX2	Exponent which permits the variation of weight WD with time to be made nonlinear in computing objective function	2.0	10
PCENT	The fixed percentage for computing PCOB in the tolerance	0.075	15
MAXN	The maximum allowable number of passes through the adjustment strategy	100	36
DEL	The fixed delta to be used for precipitation adjustments in subroutine STRAT	1 mm	29
WDEL	The fixed delta to be used for adjustments to the warp coefficients, RH and RV, in subroutine STRAT	0.01	29
WHL	Lower constraint on adjustments to RH	0.7	37
WHH	Upper constraint on adjustments to RH	1.5	37
WVL	Lower constraint on adjustments to RV	0.7	37
WVH	Upper constraint on adjustments to RV	1.5	37
ZLOW	The ratio for computing the lower constraint on precipitation in subroutine STRAT	0.5	38
HIGH	The ratio for computing the upper constraint on precipitation in subroutine STRAT	2.0	38
UCX	The fixed upper constraint on precipitation	0.	38

Other than standard input to the forecast, namely MAP computed from point rainfall amounts, and discharge (stage) observations, CHAT requires no additional data. However, the CHAT routines are designed to operate in metric units; thus, the MAP and discharge observations must be expressed in millimeters (mm) and cubic meters per second (cms), respectively.

All of the parameters, data, and variables required by the procedure are passed between the CHAT routines and the forecast program through the individual subroutine argument lists or by the following four common blocks:

```
          COMMON/MATOL/EX1,PCENT

          COMMON/MAOBJ/EX2

          COMMON/BLOT/QBL(53)

          COMMON/MASTRA/UGI2(107)OFB,MAXN,DEL,WDEL,WHL,WHH,
       1     WVL,WVH,ZLOW,HIGH,UCX,TOL,MSG,NJ,SUM,LK(53),UK(53)
```

These common statements must be inserted in the forecast program at the proper place; they have already been included in the appropriate CHAT subroutines. In addition, the variable LK must be specified as type real. Also included in the CHAT routines are all other necessary common statements that pass variables that do not appear outisde the CHAT subroutines. The variables in each of the subroutine argument lists will be described later in this chapter.

As for dimensions, all variables currently dimensioned for 53 in the subroutine listings can be changed at the user's discretion. This number is a function of the maximum duration, in intervals of 6 hours, of runoff events in the user's forecast area. Every time CHAT is used during a runoff event, it operates with the data and hydrograph from the very beginning of the runoff event up through forecast time. As CHAT is used for forecasts made down through the recession, it deals with an ever increasing portion of the runoff event until, at the very end, it is dealing with the entire runoff event. Thus, the variables in the CHAT procedure, unless specified otherwise, must be dimensioned for the entire duration of the runoff event. The current value of 53 is carried over from the research program, which was dimensioned to handle events that extended up to a maximum of fifty-three 6-hour periods. The dimensions of the simulated and blended discharge arrays, QS and QBL, must at least extend over the duration of the runoff event to satisfy CHAT's requirements. Any additional dimensioning on these variables will depend upon the design of the forecast program.

The noted exceptions to the dimensions thus far discussed are variables TB, QB, and S in subroutine INTERP. They are dimensioned to allow the usage of a maximum of 100 randomly spaced discharge observations. Once again, this value can be changed as the user deems appropriate for the observational reporting network in his area. The only restriction on re-dimensioning applies to the variables in subroutine WARP. They must remain as coded in the listings in order for the subroutine to function properly.

In order to use CHAT, the beginning of the runoff event must be defined. It is realized that there are no definitive guidelines for doing this. The manner in which the runoff event is identified, whether by the subjective judgement of the forecaster or by some sort of objective criteria in the program, will depend upon the user's preference and his particular forecast operation. No attempt has been made in this report to address the problem other than by providing some insight through examples 2 and 3 of the next chapter. Once the runoff event has begun, CHAT must be used for every forecast made during the event. The forecaster does not decide if adjustments, and hence CHAT, are necessary; the CHAT procedure is always initiated during a runoff event, and it determines if adjustments are required at that time. As will be shown later, CHAT will make no adjustments if the hydrograph derived from the data, as it is at the beginning of the forecast, agrees satisfactorily with the observations.

Since the standard data and computing interval for NWS forecast programs is 6 hours, the CHAT adjustment procedure must also operate on a 6-hourly basis. This means that, regardless of the time interval between forecasts, during a runoff event each 6-hour period that has elapsed since the last forecast must be regarded, in succession, as the "current" time for CHAT's computations. Since this "current" time will generally differ from forecast time, unless forecasts are being made every 6 hours, CHAT provides its own indexing system in the form of the variable "NFORC". NFORC represents the number of 6-hour periods that have elapsed since the beginning of the runoff event up to the period that is being regarded as the latest. In other words, NFORC is always the "current" time for CHAT's computations. If forecasts are being made every 6 hours, then NFORC and forecast time coincide. In the discussions in this report so far, for the purpose of explaining the theory with as little confusion as possible, it has been assumed that forecasts are being made every 6 hours, and thus the two terms have been used interchangeably. However, for the purpose of explaining how to use CHAT in an operational framework, it becomes necessary to differentiate between the two since forecasts are not always made operationally every 6 hours.

Regardless of the value of NFORC, CHAT always operates from the beginning of the runoff event. Its variables and data are, therefore, indexed from 1 to NFORC, where the first value is associated with the first 6-hour period of the event. Any time a simulation is made, the hydrograph is recompiled from this point. Consequently, only one set of carryover values needs to be saved, that being the values of the soil moisture and channel flow variables going into the first 6-hour period of the runoff event.

Figure 5.1 illustrates the way in which the CHAT routines link to the normal forecast operations. The steps shown in the diagram must be repeated for each successive 6-hour period that has occurred since the last forecast. This figure and the concepts discussed in the last few pages are perhaps better explained through an example. For instance, in a case in which forecasts are being made daily at 12Z, four new 6-hour MAP values are available for input to the forecast each time: the MAP of 18Z on the previous day (herewith referred to as Day 1), and the MAPs of 00Z, 06Z, and 12Z of the current day (Day 2). Starting at the top of the diagram, it is assumed that all preliminary data processing (MAP computations) has been completed prior to this point. Suppose 18Z is the first period of a runoff event. NFORC is then set equal to 1 and becomes associated with the time of 18Z; the values of the soil moisture and channel flow variables at this time are saved as carryover, and the program branches to the CHAT procedure.

The first step in the strategy is to call subroutine INTERP, which interpolates between discharge observations made at random times and determines the value at each 6-hour ordinate corresponding to the ordinates of the simulated hydrograph. Three items must be passed to the subroutine in the argument list:

```
CALL INTERP(NB,TB,QB)
```

where NB is the number of observations available for input at the current time NFORC, TB(1) to TB(NB) are the times, in hours, of the observations, and QB(1) to QB(NB) are the observed discharges at each of the times in the TB array. TB(1) must be zero or otherwise it will be set to zero inside the subroutine, and it coincides with the first 6-hour ordinate on the simulated hydrograph. The observations must be in chronological order. Even though, at forecast time, discharge observations may be available up through 12Z, only observations up to the time of NFORC are passed to the subroutine for this pass through the strategy. The reason for this is to prevent discharge observations that occur subsequent to the time of the latest MAP value that is used in the soil-moisture computations from being included in the computations of the objective function. Otherwise, unjustified changes may be made to the MAP values up

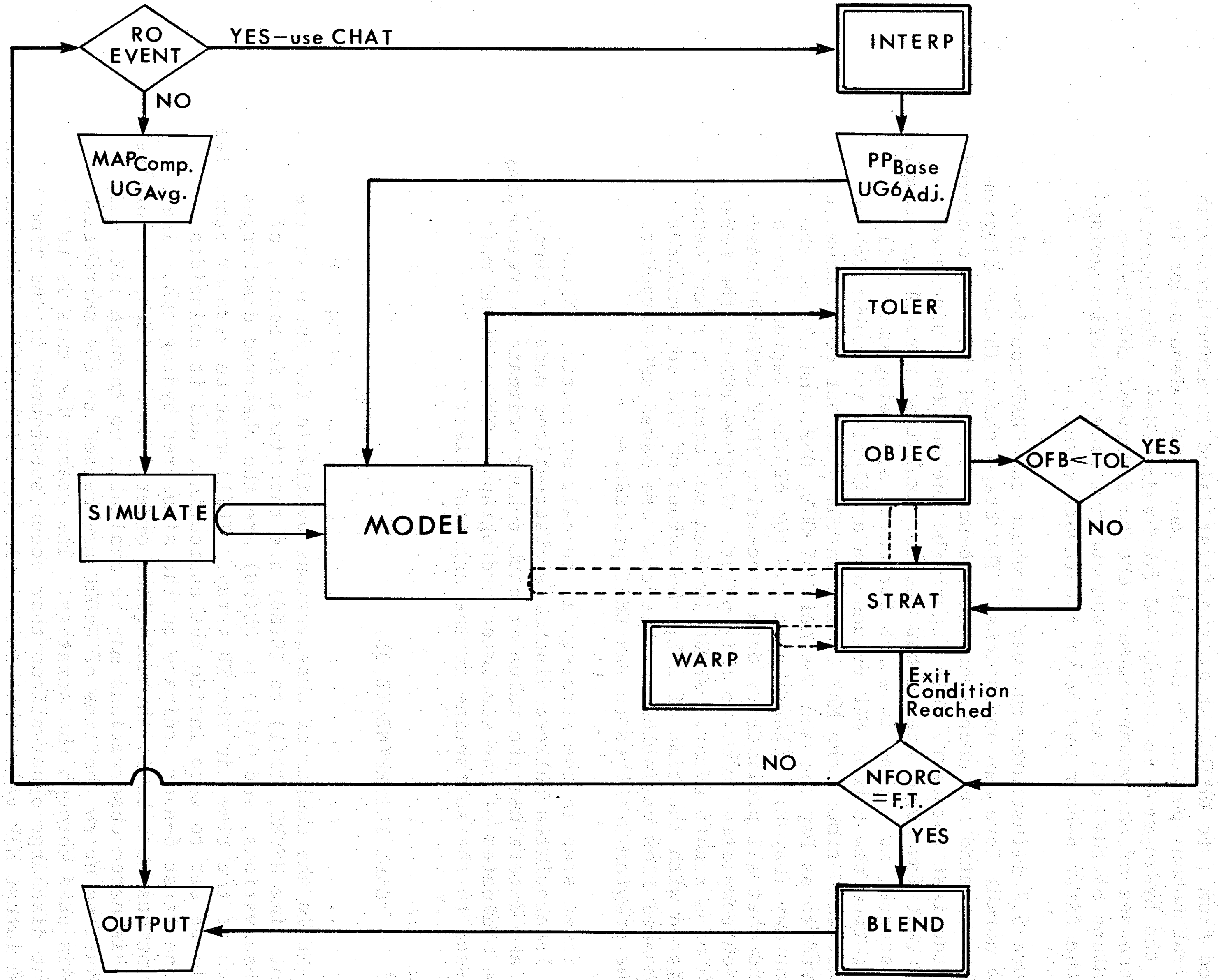


Figure 5.1--Schematic of forecast procedure with CHAT adjustment strategy

through the time of NFORC based on the degree of fit with observations that include the effects of precipitation that the model has not yet seen. While observations cannot be used subsequent to NFORC, they need not necessarily be available up to the time of NFORC either. INTERP computes the quantity NOB, which is the number of the last 6-hour ordinate prior to, or at the time of, the last discharge observation, and the objective function is computed only as far as NOB. Situations will arise where the latest observation was made more than a couple of hours later than time NFORC, but the last observation prior to that one was made long before time NFORC. In such a case, the forecaster should estimate the discharge at time NFORC and include that estimate as the latest observation. When, one or more periods later, the actual observation can be used, any such estimates should be deleted from the QB array.

The next step is to make what is termed the "base" simulation. This simulation is a result of using precipitation values PP(1) to PP(NFORC-1), as adjusted during period (NFORC-1) plus the current computed MAP value, PP(NFORC), and the unit graph ordinates, UG6(36), as adjusted during period (NFORC-1). If no adjustments have been made prior to period NFORC, then the PP array contains the original computed MAP values, and the unit graph, UG6(36), is still the <u>average</u> basin unit graph. (For this use, the average unit graph must be defined by 6-hour instantaneous ordinates whereas for subroutine WARP, it has to be defined by 2-hour ordinates - a point that was discussed earlier in this chapter.)

For the present example, with NFORC equal to 1 and no adjustments having been made thus far in the event, the computed MAP of 18Z is put into the PP(1) position and UG6(36) is set equal to the average basin unit graph. If QPF is being used, its N values must be placed in the PP(NFORC+1) to PP(NFORC+N) positions of the array. As mentioned earlier, QPF can be used in conjunction with the CHAT procedure but CHAT will make no adjustments to it. If no QPF is used, the future precipitation is set equal to zero. The base simulation is then made by calling subroutine MODEL, passing to it these input arrays:

```
CALL MODEL (PP,UG6,QS)
```

where PP and UG6 are as defined above and QS is the base simulation array that MODEL returns. MODEL is not one of the six CHAT subroutines but instead is a subroutine that must be constructed by the user for use with his particular forecast program. CHAT passes the precipitation and unit graph arrays to it, MODEL calls whatever forecast program modules are necessary to produce a hydrograph from the respective input arrays, and places the ordinates of this hydrograph in the array that is accessed by the CHAT procedure. In this way CHAT remains independent of the particular hydrologic model that is used to produce the hydrograph.

After MODEL returns the base simulation, the CHAT strategy decides if it is in satisfactory agreement with the observations up through ordinate NOB. This is determined by first calling subroutine TOLER to compute the tolerance at the current time NFORC:

```
CALL TOLER(NFORC,QS,PP,TOL)
```

where NFORC,QS,PP are as defined earlier, and TOL is the tolerance, and then by calling subroutine OBJEC to compute the objective function for the base simulation:

```
CALL OBJEC(QS,OFB)
```

where OFB is the objective function for the base simulation. A comparison must then be made between OFB and TOL: if OFB is less than or equal to TOL, the base simulation agrees satisfactorily with the observed hydrograph and adjustments by CHAT are not necessary. On the other hand, if OFB is greater than TOL, the base simulation is <u>not</u> satisfactory and CHAT must make adjustments to the input arrays.

The adjustments are initiated by calling subroutine STRAT. A detailed description of the adjustment strategy that is used by this subroutine has already been presented in Chapter 4. It is sufficient for the purposes of the present discussion to simply describe the variables in its argument list:

```
CALL STRAT(NFORC,RH,RV,UG6,PP,QS)
```

where NFORC is the current 6-hour period, RH and RV are the horizontal and vertical warp coefficients, UG6 is the unit graph, and PP is the precipitation array. When STRAT is called, these variables contain values that are associated with the base simulation. Since NFORC is equal to 1, RH and RV must be initialized to the value of 1.0 before being passed to the subroutine. When the return is made from the subroutine, RH, RV, UG6, and PP have automatically been updated inside STRAT to reflect the adjustments CHAT made, and the adjusted hydrograph is returned in array QS.

In the diagram subroutine STRAT is connected to subroutines MODEL, OBJEC, and WARP by dotted lines, whereas all the other connecting lines are solid. This distinction is made to indicate that the call statements to these subroutines are provided within subroutine STRAT rather than by the forecast program. All operations associated with making adjustments are handled automatically within this subroutine, and a return is not made from STRAT until one of three conditions exists:

MSG = 1: no reductions were made in the objective function on the last pass through the adjustment strategy, and the objective function is still greater than the tolerance

MSG = 2: the objective function is less than the tolerance

MSG = 3: the number of passes allowed through the adjustment strategy MAXN, has been exceeded and the objective function is still greater than the tolerance

The variable, MSG, is set within the subroutine to indicate which exit condition is used and passed back to the forecast program through a common block.

One more variable must be discussed in connection with subroutine STRAT. The function of computing constraints on the precipitation is performed within this subroutine. Thus, even if adjustments are not necessary, STRAT must still be called to compute the constraints for the current MAP value, PP(NFORC), although this is not shown on the diagram. Constraints for the MAPs of 6-hour periods prior to NFORC will have been computed when each of those periods was regarded as NFORC, and therefore, do not have to be recomputed. If the subroutine is to be used only for this purpose, a flag, NJ, must be set to zero prior to the call. Otherwise, NJ must be set equal to 1 and the subroutine will be used to make adjustments as well. The constraints, LK(53) and UK(53), are used within STRAT, but they are also commoned with the forecast program so that they can be saved between forecasts.

At this point, CHAT has completed its operations for period NFORC, or 18Z in this case. Let us assume that the base simulation for 18Z was <u>not</u> satisfactory and subroutine STRAT was called, with NJ = 1, to make adjustments. The PP(1) position now contains the adjusted MAP value of 18Z, UG6(36) is the revised unit graph based on the adjusted values of RH and RV, and the QS(53) array contains the adjusted hydrograph that corresponds to the new PP and UG6 arrays. If NFORC does not coincide with forecast time (12Z), as it does not in this case, another pass is made through Figure 5.1 with NFORC incremented to 2 and associated with the time of 00Z of Day 2.

The first decision on the second pass is to determine if 00Z is still part of the runoff event. The use of the CHAT procedure requires the definition of the end of the runoff event as well as the beginning. Note in the schematic that if a 6-hour period is not part of the runoff event, the forecast computations are performed in the usual manner, using the computed MAPs and the average basin unit graph, and are unaffected by the CHAT routines.

Assuming the runoff event has not ended by 00Z of Day 2, INTERP is once again called with the observations that are available up to time NFORC, taking into account the fact that NFORC is now six hours later. INTERP must always be called even if the discharge observations coincide with 6-hour ordinates because it computes quantities that are used by subroutine OBJEC.

Next, the base precipitation array is constructed by placing the computed MAP of 00Z into the PP(NFORC), or PP(2), position. PP(1) contains the 18Z MAP value as adjusted during the previous pass. This array along with the adjusted unit graph, UG6, is then passed to subroutine MODEL for computing the base simulation at time 00Z. The user is reminded that when using CHAT, all simulations are recomputed from the beginning of the runoff event. Therefore, when MODEL calls the appropriate forecast program modules to produce the hydrograph, the computations in these modules must originate from the set of carryover values that were saved at the beginning of the event.

The remainder of the steps in the diagram are executed for NFORC = 2 in the same manner as described for NFORC = 1. If the base simulation is not satisfactory, STRAT is called and given the opportunity to once again adjust UG6 and PP, with PP now containing two MAP values. As before, these arrays are updated upon return from the subroutine and are subsequently used as input for the base simulation of the next 6-hour period, 06Z.

This process is repeated for each remaining 6-hour period until NFORC coincides with forecast time, at which point a forecast must be issued. In this example NFORC coincides with forecast time, 12Z on Day 2, when it reaches the value of 4. At that time, the forecasted hydrograph from the CHAT procedure is located in array QS, and the PP and UG6 arrays contain respectively the four MAP values and the unit graph ordinates that produce this hydrograph. Presumably, this hydrograph agrees more closely with the partial observed hydrograph than would have the hydrograph derived from the original data. To resolve the remaining difference, hopefully minor, that might exist between the adjusted hydrograph and the observations, subroutine BLEND is called, which merges the two hydrographs within a pre-determined number of ordinates.

```
CALL BLEND(QS)
```

where QS is the adjusted hydrograph. The output from BLEND is the blended hydrograph, QBL, which is the actual forecast from the forecast program and CHAT combined.

The output routines of the forecast program are used to display the CHAT-adjusted hydrograph. The user must program to bring out whatever additional CHAT information he wishes to examine. In the research work the following displays and information were found to be useful at each forecast time (which was every 6 hours):

1. "raw" simulation from original data
   original precipitation data
   objective function for raw simulation

2. base simulation
   RH and RV for base simulation
   precipitation for base simulation
   objective function for base simulation
   tolerance at time NFORC

3. adjusted simulation
   adjusted RH and RV values
   adjusted precipitation
   objective function for adjusted simulation

4. a message based on the value of MSG to indicate which exit condition from STRAT was used

It is imperative that the forecast program interrogate MSG. In the case where MSG equals 1 or 3, CHAT is unable to produce, by adjustments to the input, a hydrograph that agrees within acceptable limits with the observations. It may not be desirous to route this hydrograph downstream, and therefore, some sort of forecaster intervention must be permitted at this time. Whatever type of revision is used, the forecaster must refrain from interfering with CHAT's function--that of adjusting the precipitation. CHAT presumably has adjusted it in the best manner possible, and the forecaster should not attempt to change it and re-run the model. If he chooses to revise the simulation, using any rationale that seems appropriate, he should revise only the output hydrograph and not change the state variables of the model.

One more point concerning forecaster intervention should be mentioned. The CHAT output is a hydrologic analysis of what has happened on the catchment as a result of rainfall that has already occurred rather than what appears is going to happen if the rainfall continues. If the forecaster thinks that there is going to more rain, he should not raise the forecast; he should, instead, enter QPF in the PP array and allow CHAT to handle it.

After each forecast is made, the following CHAT variables must be saved, in addition to the carryover, for input to the next forecast:

NFORC,PP(53),UG6(36),RH,RV,SUM,LK(53),UK(53).

Suppose the next forecast is made at 12Z on Day 3. If the runoff event is still continuing, the CHAT variables listed above (values at forecast time 12Z-Day 2) are retrieved from storage and used to begin the next pass through Figure 5.1. NFORC, currently equal to 4, is incremented to 5 and becomes associated with the time of 18Z on Day 2. The base precipitation array is prepared by inserting the computed MAP of 18Z-Day 2 into the PP(5) position; the first four positions, PP(1) to PP(4), contain 6-hour MAP values from the beginning of the event (18Z-Day 1) as adjusted when NFORC was equal to 4. Likewise, UG6, RH, and RV contain the final adjusted values from the previous pass. With this data, the base simulation is made for NFORC = 5, and so forth on through the strategy. Once again, the simulation originates from the beginning of the runoff event, and STRAT has the option of adjusting precipitation values 1 through NFORC.

The forecast operations continue in this manner until the forecaster flags the end of the runoff event, at which time control returns to the normal forecast procedure. The values of the soil moisture variables at the end of the last pass through the CHAT procedure reflect all the changes that were made to the input, and thus the hydrograph, during the runoff event, and these values are carried into future simulations. Therefore, CHAT has fulfilled its requirements of adjusting the model's state variables as well as the model's output.

It has been stated that each 6-hour period during the runoff event must be regarded, in turn, as the current period for CHAT's computations, but the reason for this has not been explained. One of the unique features of the CHAT adjustment strategy is that it will adjust only those precipitation periods that are contributing most heavily to the runoff at the current time. (This feature has been discussed at length on pages 30-31.) As "current" time progresses through the runoff event, the critical precipitation periods change also, so that at one point or another each 6-hour precipitation period will have been in the "critical" position and been able to be adjusted. However, if "current" time progresses at intervals larger than 6 hours, one or more of the 6-hour precipitation periods will never be in the critical position in relation to "current time," and consequently, will not be properly adjusted. Hence, the reason for <u>each</u> 6-hour period being treated, in succession, as the "current time."

It is hoped that the discussions of this chapter will provide the necessary guidelines for implementing the CHAT adjustment procedure in the user's forecast program. Only those specifications that are crucial to the proper use of the procedure have been provided in order to allow as much freedom as possible in adapting this procedure to the user's particular forecast program.

6. EXAMPLES

During the research phase of the project, the CHAT procedure has been tested on many runoff events from various headwater basins. The analyses are of a conceptual rather than a statistical nature; thus, no attempt has been made to study a "statistically significant" number of events. The primary purpose of the studies has been to acquire a knowledge of the characteristics of the CHAT procedure. It is believed that this type of knowledge is transferable to other events as well. From these studies, six examples have been selected for this report to illustrate the manner in which the procedure operates. These particular events were chosen because they demonstrate CHAT's performance under a variety of conditions on several basins of highly different characteristics.

To test the CHAT procedure, the CHAT routines were linked to a hydrologic model consisting of the Sacramento soil moisture accounting routine and a unit graph operation for distributing the runoff in time. For each runoff event, forecasts were made with this model every six hours as in a real-time forecasting operation. Thus, each example consists of a series of plots that illustrate the behavior of the procedure at various forecast times. The vertical dashed line identifies the forecast time, NFORC, for each plot. The ordinates along the abscissa are successive 6-hour periods from the beginning of the runoff event. In the legend, the "raw" simulation refers to the hydrograph produced by the hydrologic model using the reported data without any adjustments from CHAT. The "adjusted" hydrograph is the product of the CHAT strategy. The actual forecast from the forecast program in conjunction with the adjustment procedure is the "blended" hydrograph, obtained by merging the available portion of the observed hydrograph into the adjusted hydrograph within a pre-determined number of ordinates.

The rainfall profile for the event is displayed in the upper left corner of the illustration. Accumulative amounts, in mm, are plotted every six hours up to current time, NFORC, for both the "raw" and "adjusted" precipitation. The number on each 6-hour segment is the precipitation that occurred during that 6-hour period, or in the case of the adjusted graph, the value to which CHAT adjusted the 6-hour amount. No QPF was used in any of the examples presented in this report.

Directly beneath the precipitation plot are the adjusted values of the warp coefficients, RH and RV, that were used to warp the average unit graph. The warped unit graph resulting from these values was used in producing the adjusted hydrograph.

Each example is accompanied by discussions at each forecast time of the hydrologic conditions and the subsequent behavior of the CHAT procedure. The decisions made by CHAT have been analyzed according to a philosophy in decision-making theory expressed by Tribus (1969). If any decision involves risk, it is always possible that a good decision can lead to a bad outcome and that a bad decision can lead to a good outcome. Therefore, it is necessary to evaluate a decision on the basis of whether or not it represents a logical analysis of the information available to the decision maker at the time, and not on the outcome of the decision. It is with this philosophy that the CHAT adjustment procedure must be evaluated. The rationality of its decisions should be determined by comparing the CHAT adjustment to what an intelligent and experienced, but not clairvoyant, forecaster would have done under the same circumstances. Verifications of the peaks of the CHAT-adjusted hydrographs cannot be used as an effective measure until the rainfall for the runoff event has stopped. If the adjustment results in a good forecast, so much the better, but this is not the principal criterion in judging the performance of the technique. As stated earlier in Chapter 1, the two requirements the CHAT procedure must fulfill are that the soil moisture accounting variables be adjusted along with the output, and that the adjusted output be at least as good as that which a skilled human forecaster could produce subjectively.

Example 1

Example 1 is a runoff event that occurred on Bird Creek near Sperry, Oklahoma, on July 2, 1976. It illustrates the performance of the CHAT procedure for a case in which the raw simulation and the observations differ greatly.

NFORC 6: The raw simulation is rising in response to 33 mm of precipitation but the observations are not. CHAT lowers and delays the rise somewhat.

NFORC 7: An additional 31 mm of rain has fallen in the past 6 hours, and the raw simulation is rising rapidly. The river is still not responding, and CHAT lowers the simulation to agree with the observations.

NFORC 8: The rain has stopped. The raw simulation is showing a rise from 7 cms to 180 cms, an increase of 2500 percent, and has been continually rising for the last 18 hours. Yet, the observations show no rise at all. CHAT concludes that there has been no precipitation in the catchment, an unlikely but not impossible condition in Oklahoma in July. The action is drastic, but not ridiculous. A prudent forecaster might well reason similarly and would certainly refrain from issuing a forecast of a sizeable rise.

NFORC 9: The rain has started again and the river begins to rise slightly. CHAT acknowledges that a small rise is probable at this time.

NFORC 10-12: During these periods the river continues to rise. An additional 37 mm of rain has occurred in the past 24 hours. The CHAT simulations are repeatedly increased at the successive forecast times, partly in response to the additional rainfall, and partly because the observations indicate that the downward revisions made earlier may have been too drastic. The initial burst of 64 mm had been reduced to 0 at NFORC 8, but by the end of the event, CHAT restored 19 mm.

NFORC 13-17: There has been no additional precipitation. CHAT continues minor upward adjustments to the simulations in response to a continued rise in the observations to a peak 24 hours past the time that the raw simulation indicates the peak should have occurred.

NFORC 23: The CHAT procedure continues to operate past the peak and on down the recession so that the soil moisture variables will be updated at the end of the runoff event. By the end of the event, the total surface runoff for the raw simulation was 46.1 mm, which CHAT adjusted downward to 20.7 mm. The actual observed surface runoff was 22.6 mm.

In summation, early in the rise CHAT over-reacted somewhat in the early downward revision and had to revise upward in light of future events. However, CHAT was dealing with an event in which the raw simulation was predicting a major flood 7 feet above flood stage. The highest stage reached, in fact, was slightly below flood stage. CHAT, at all times, produced adjusted hydrographs which peaked below flood stage. It is felt that a human forecaster could not have handled this situation in a more apt manner, and consequently, CHAT has satisfied the requirements that were established for the procedure.

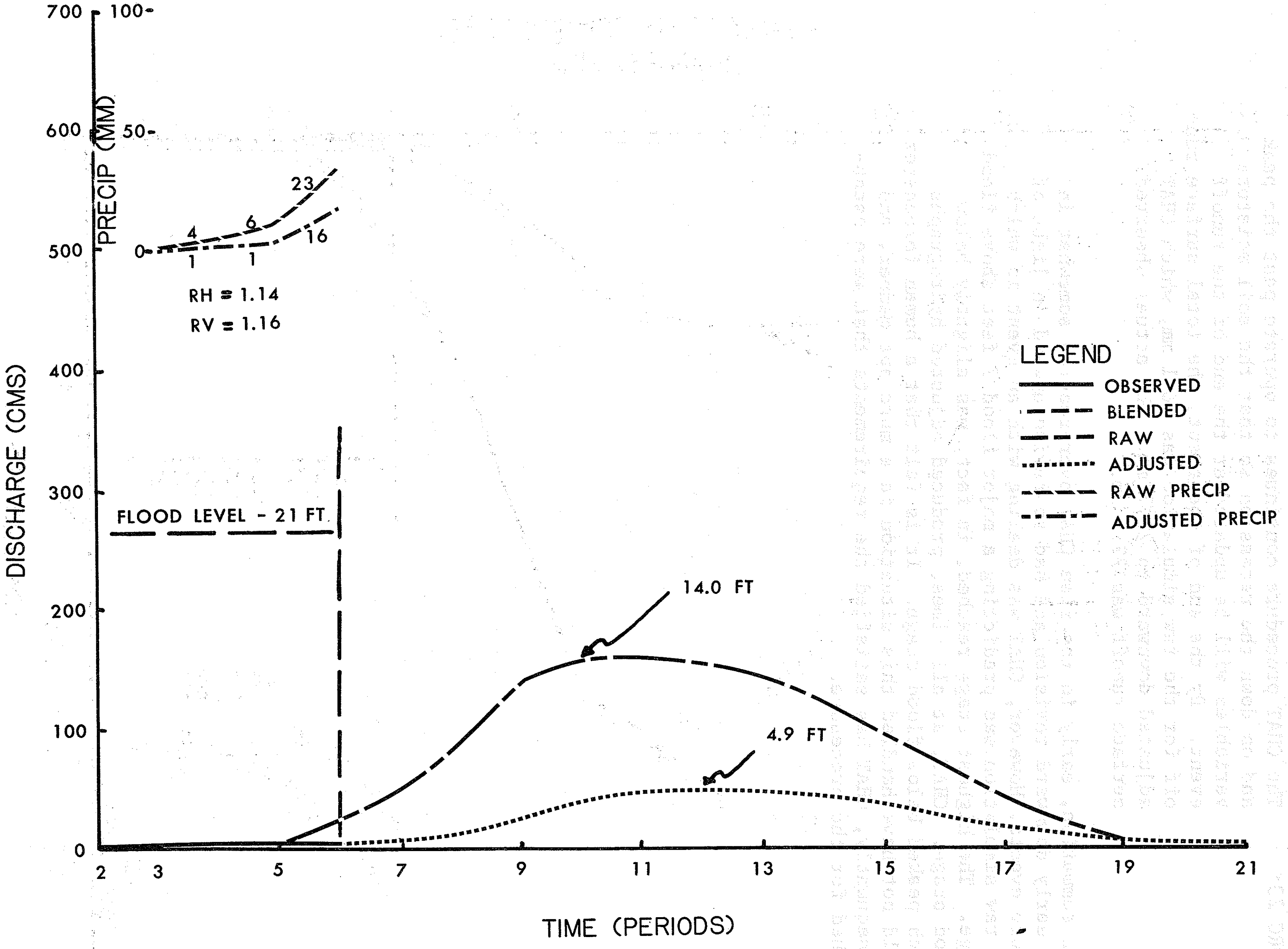


Figure 6.1--Example 1, NFORC=6

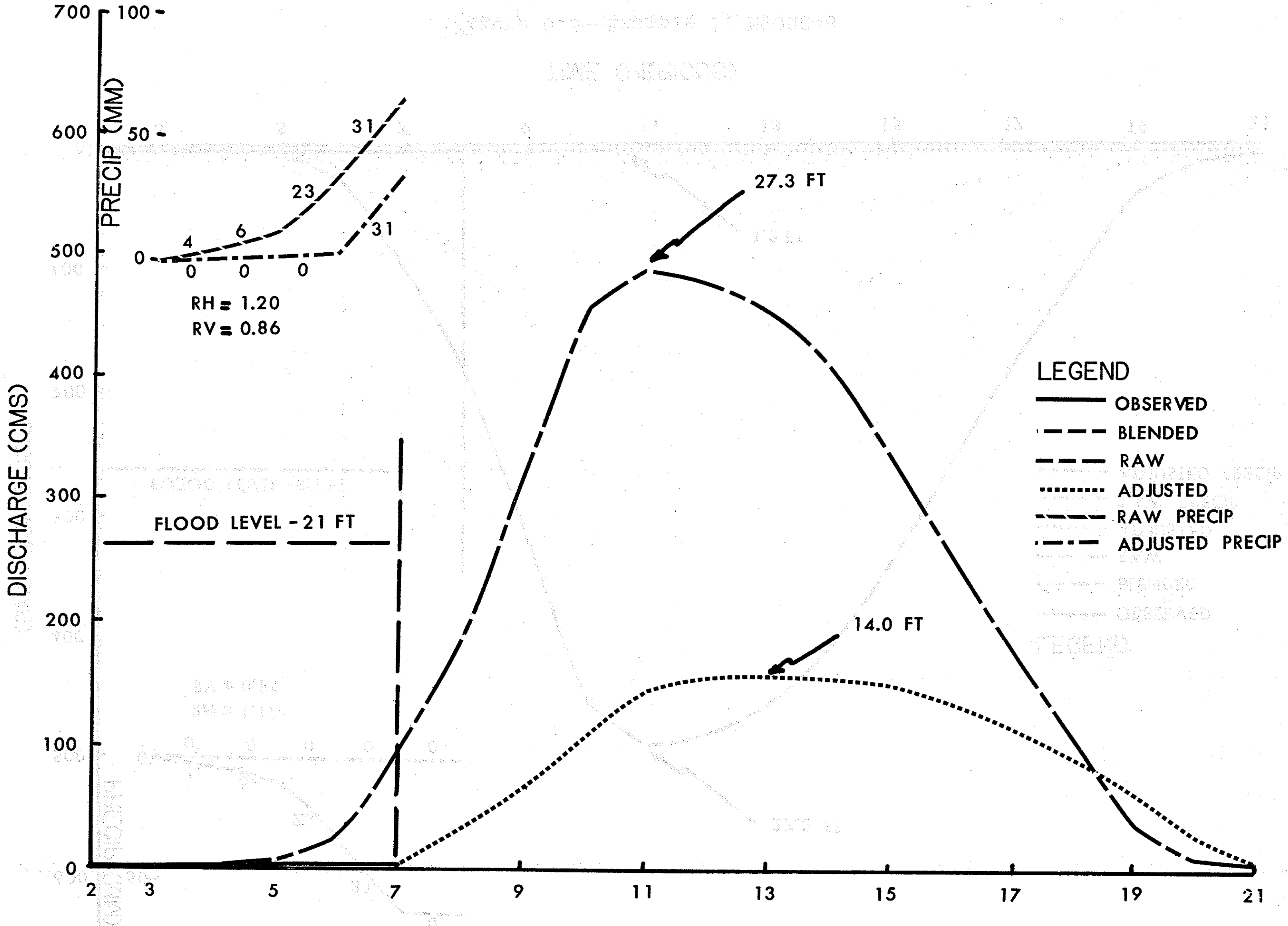


Figure 6.2--Example 1, NFORC=7

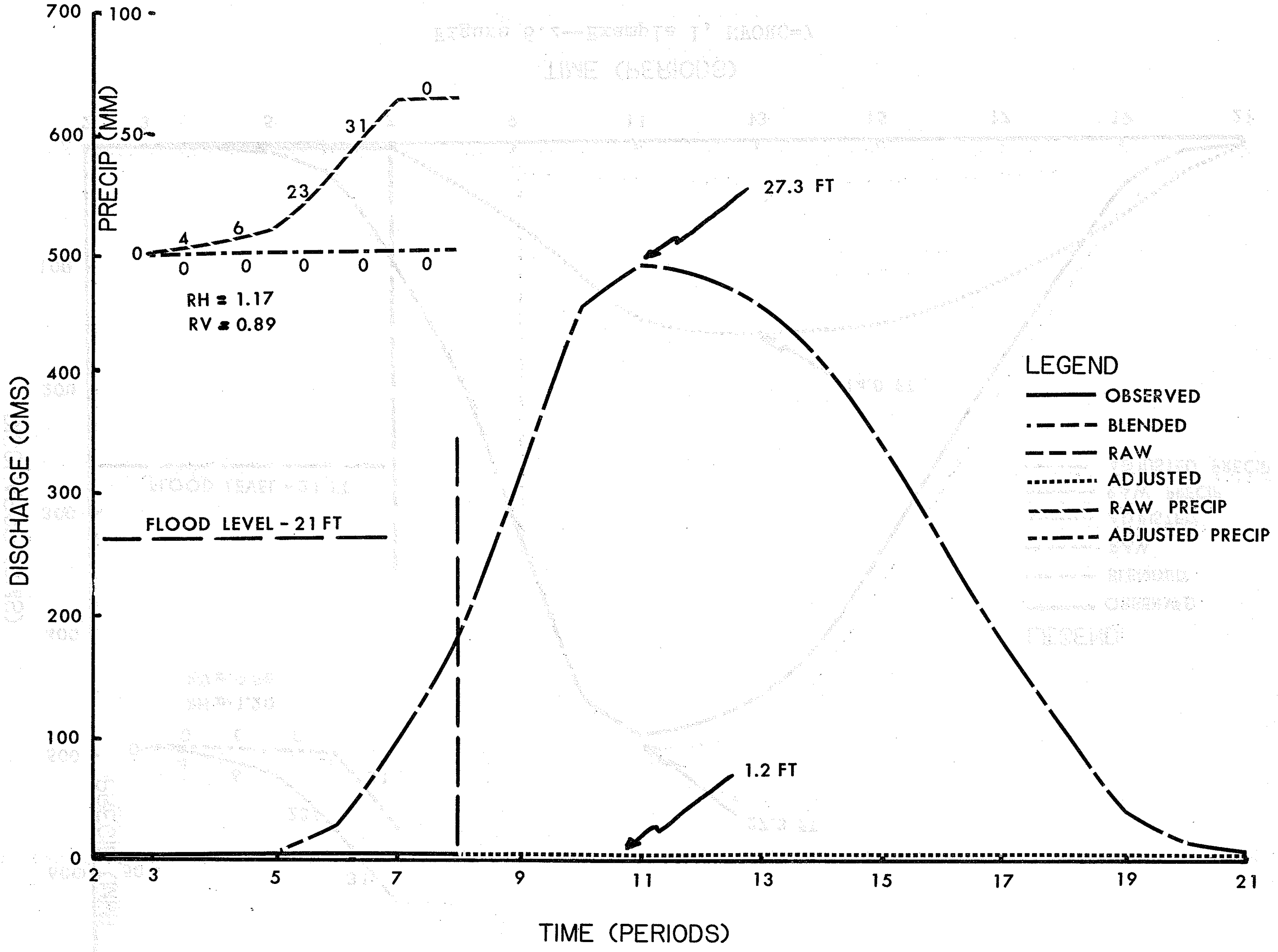


Figure 6.3--Example 1, NFORC=8

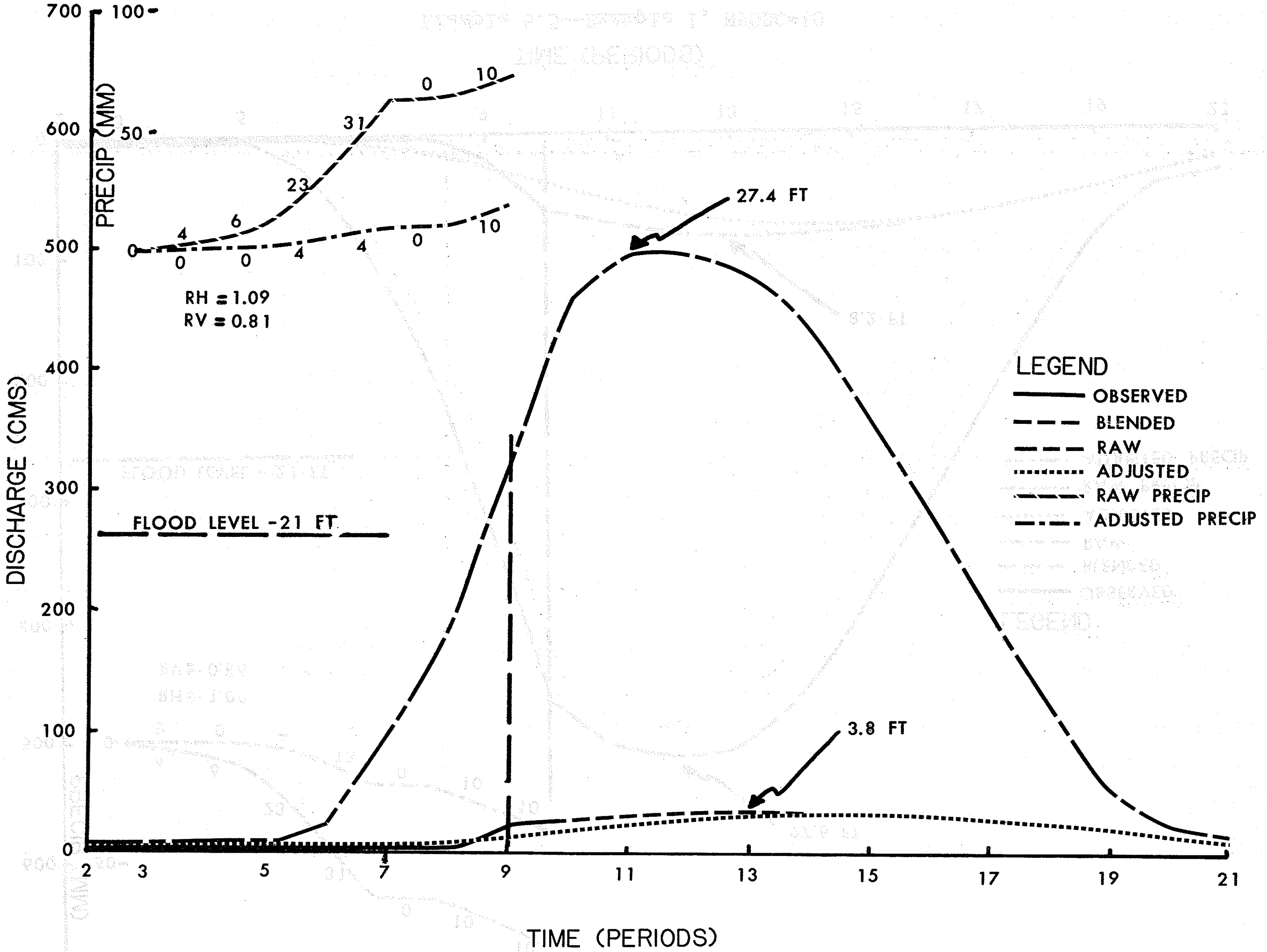
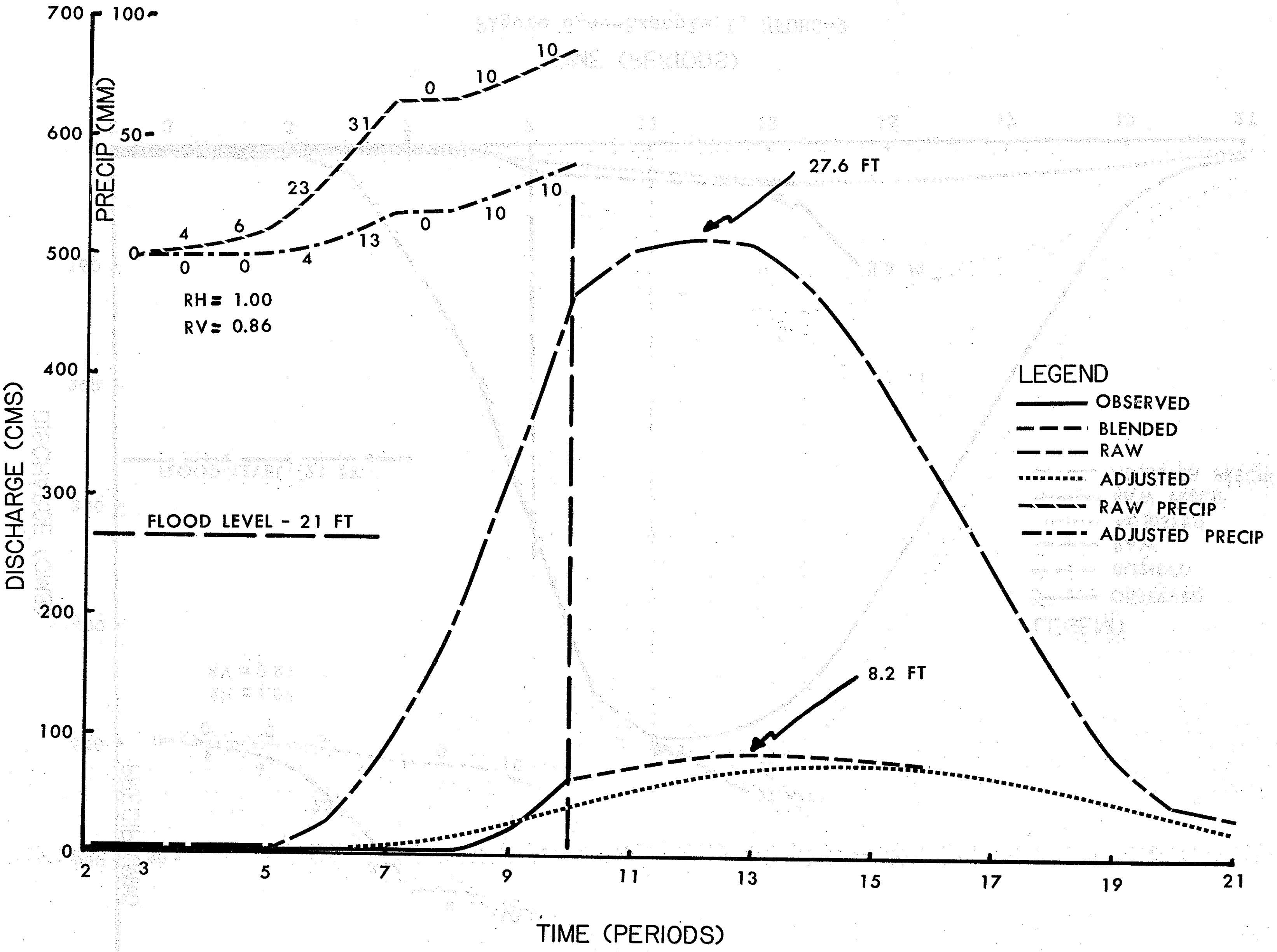


Figure 6.4--Example 1, NFORC=9



Example 6.5--Example 1, NFORC=10

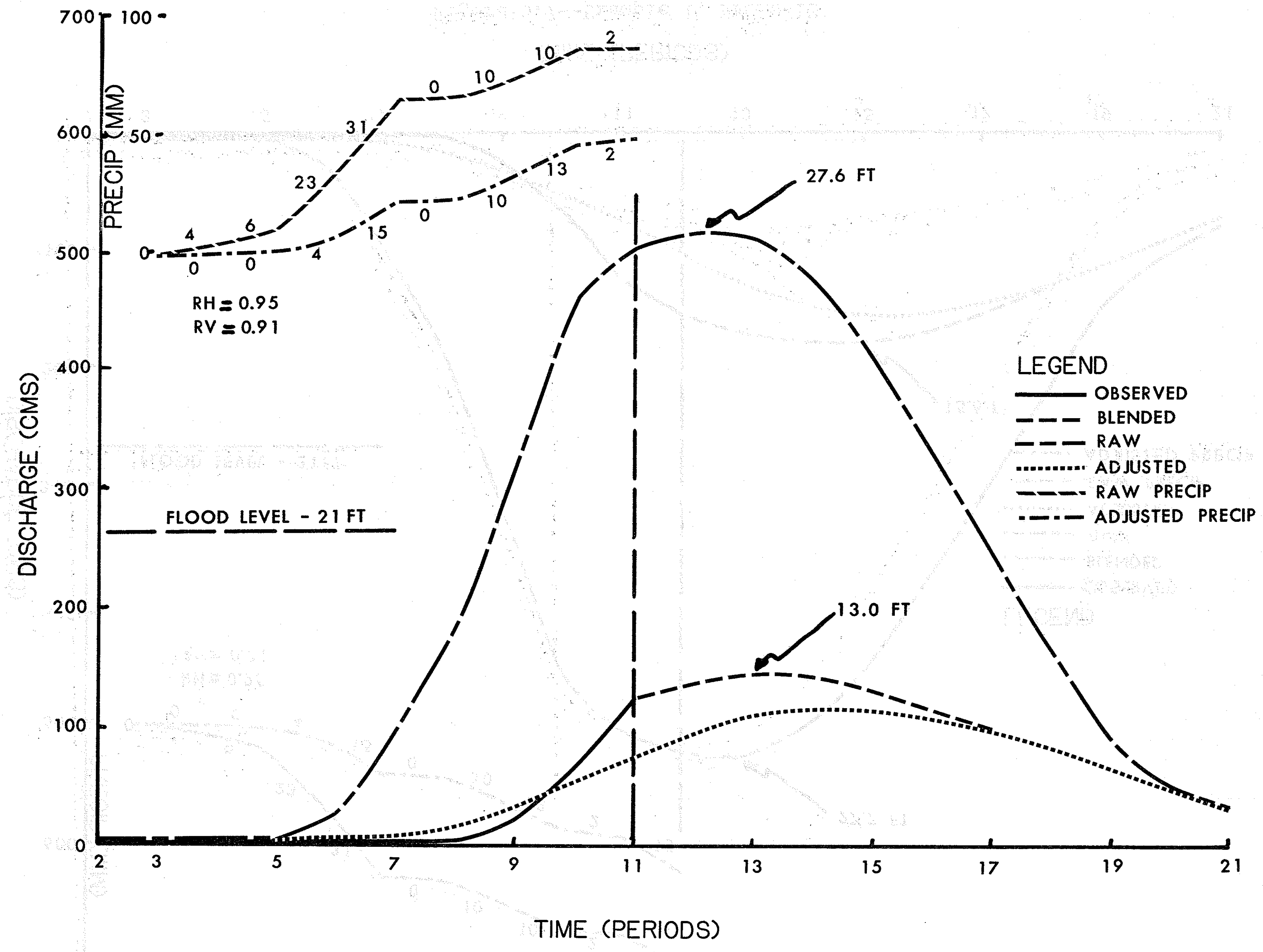


Figure 6.6--Example 1, NFORC=11

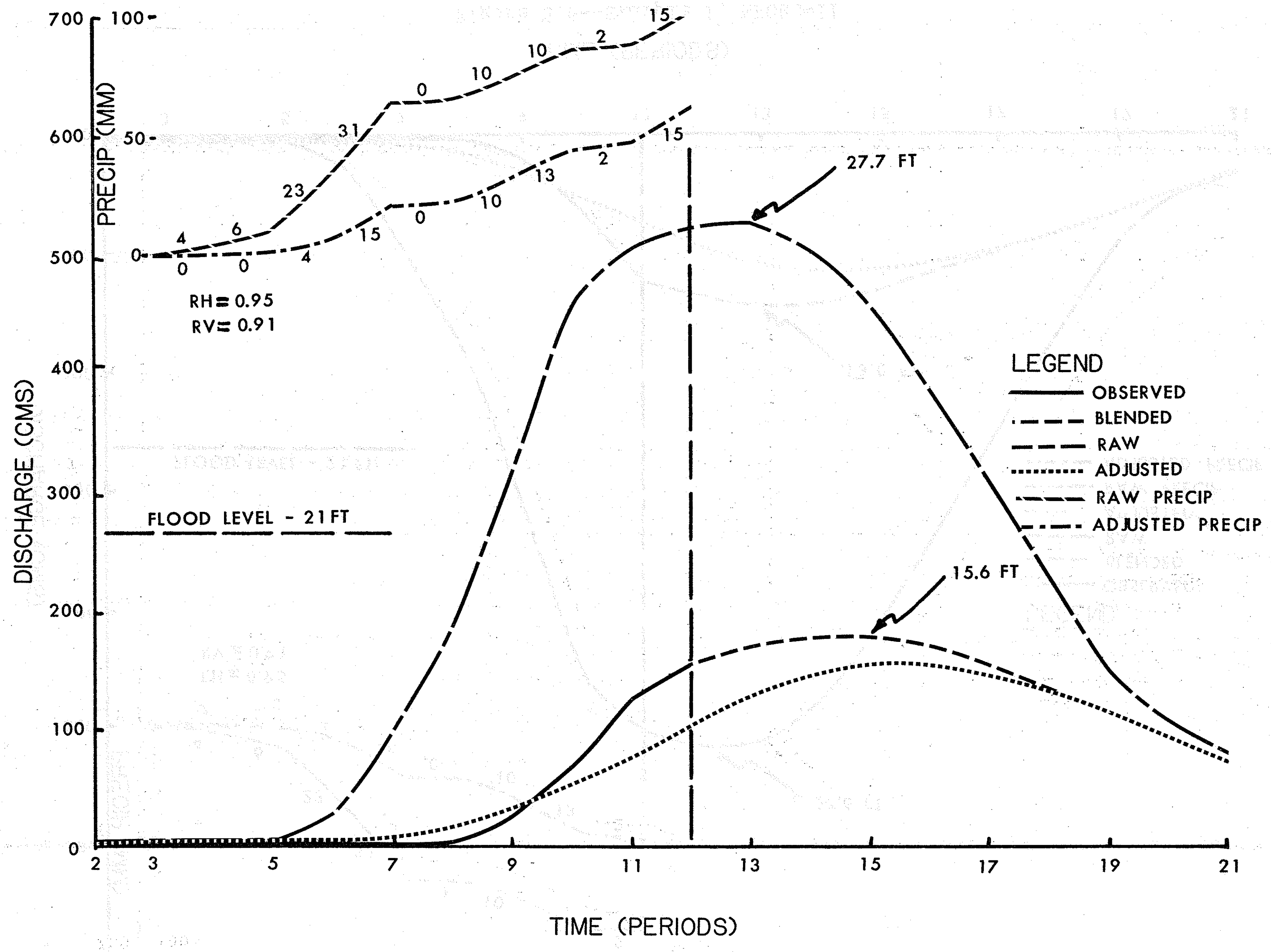


Figure 6.7--Example 1, NFORC=12

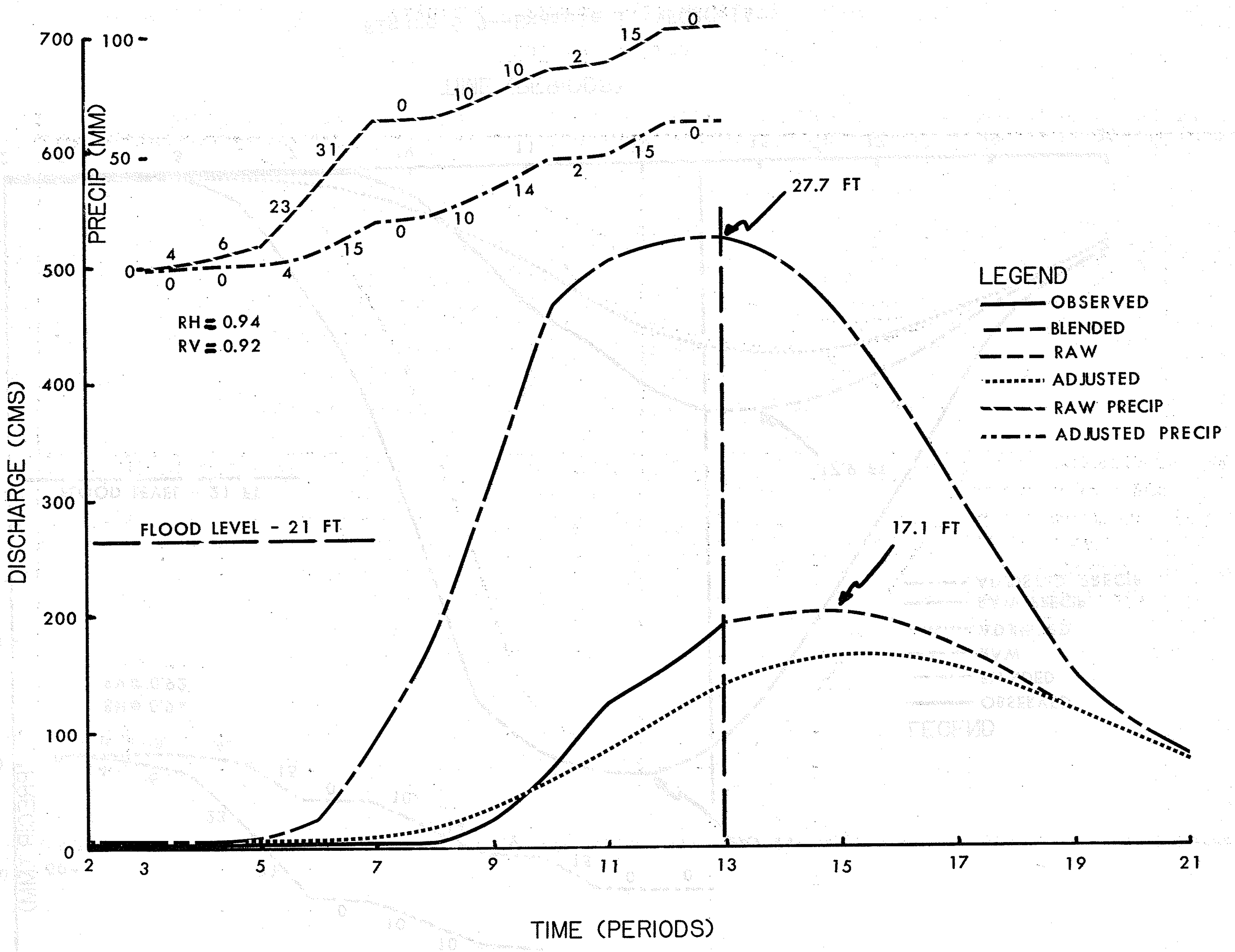


Figure 6.8--Example 1, NFORC=13

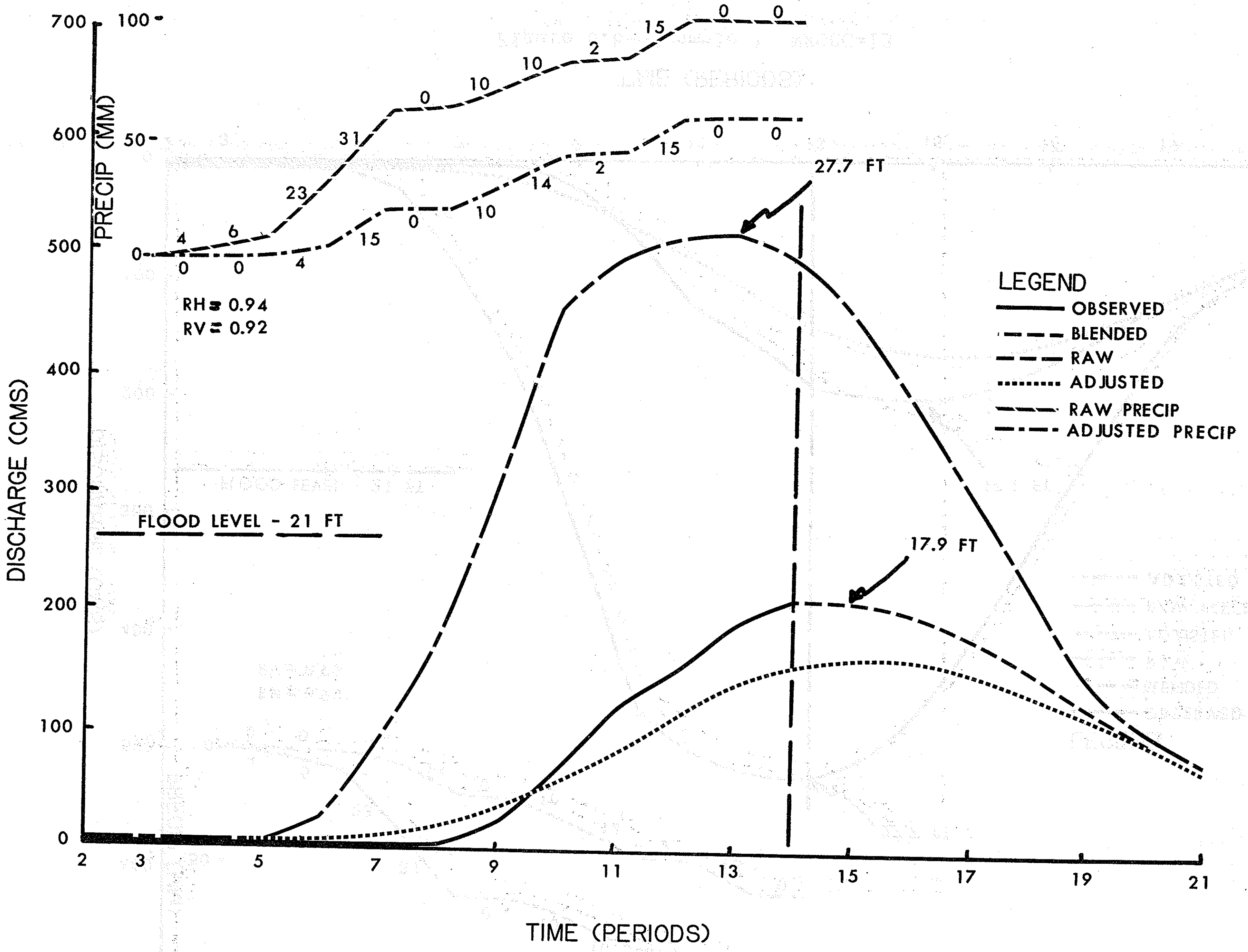


Figure 6.9--Example 1, NFORC=14

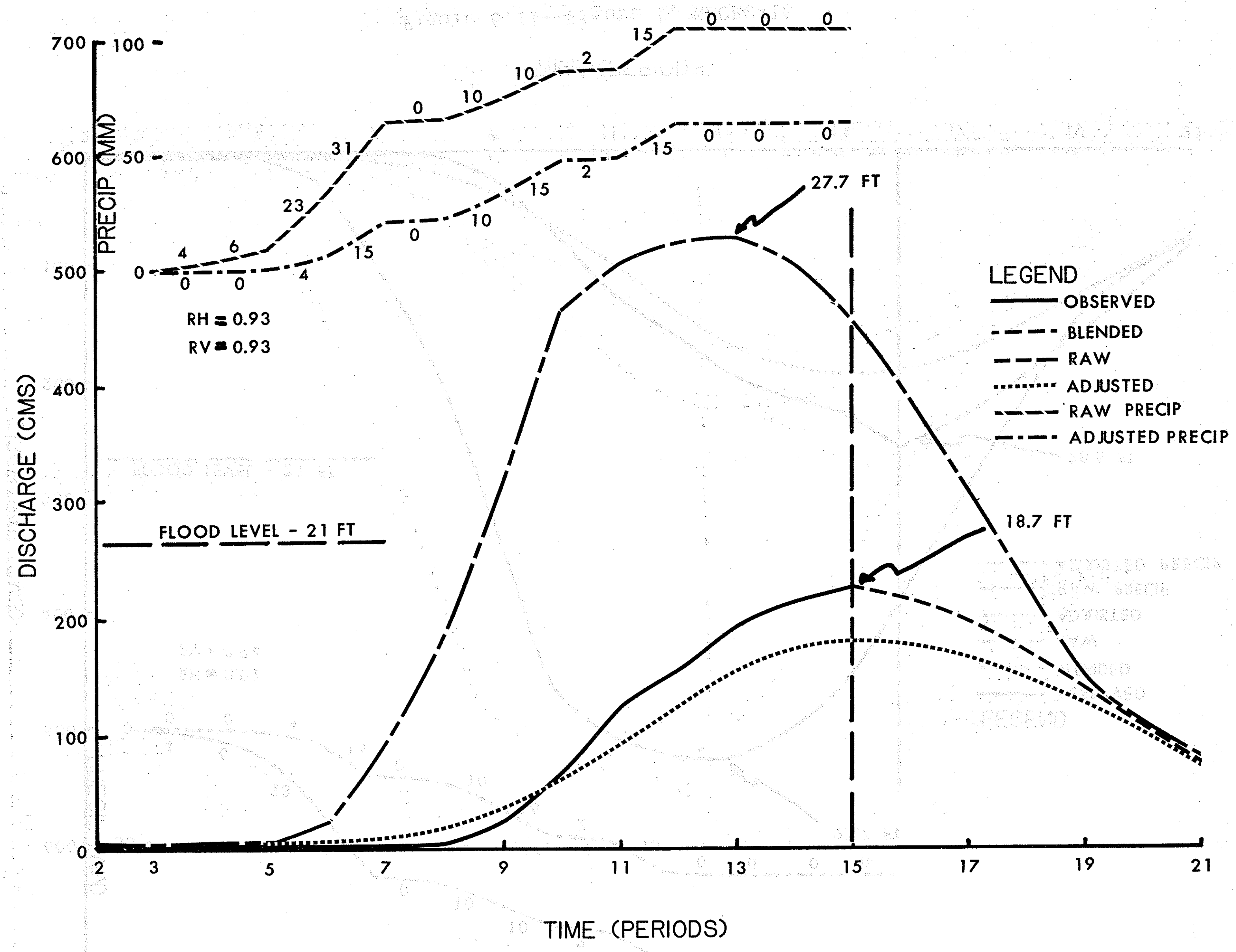


Figure 6.10--Example 1, NFORC=15

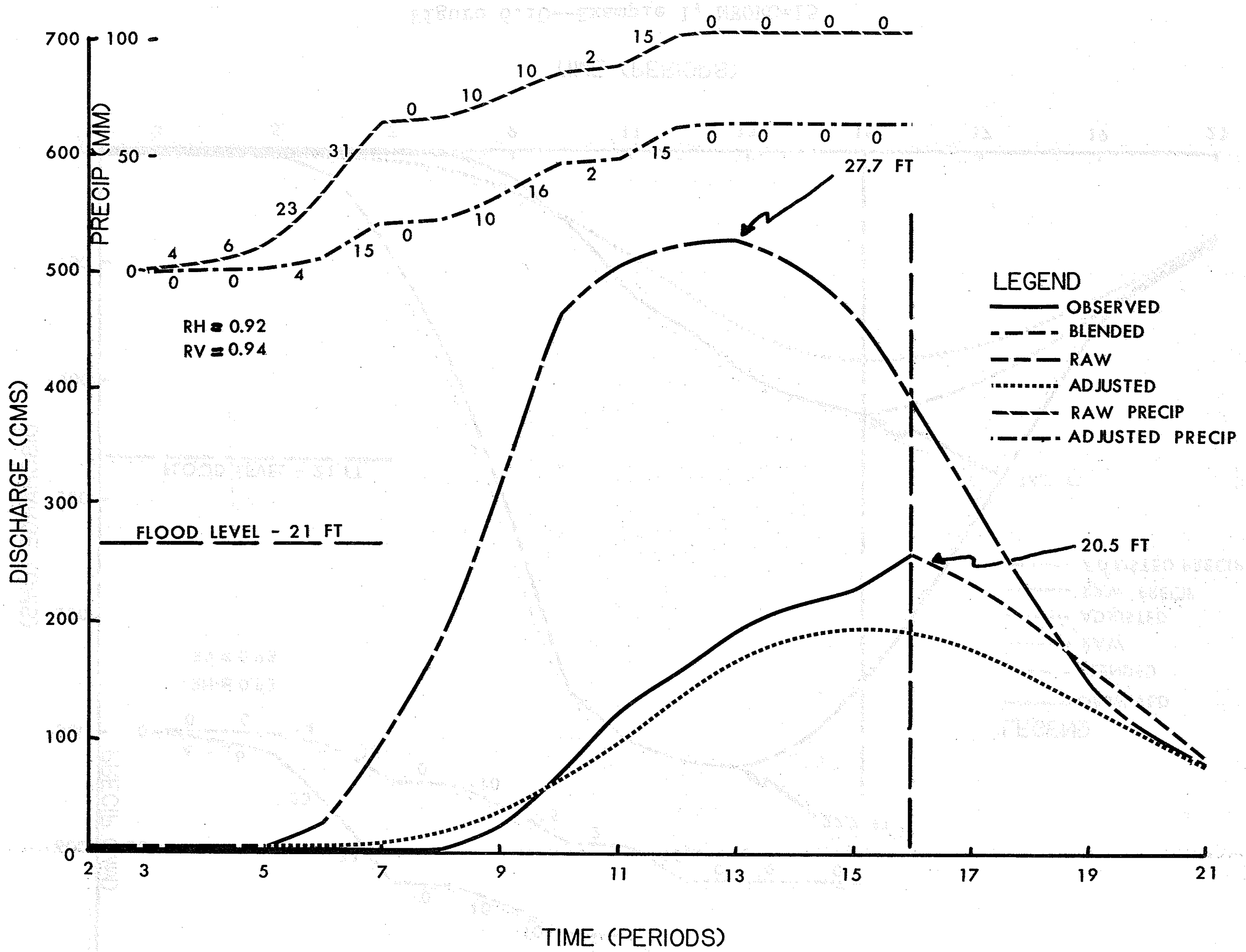


Figure 6.11--Figure 1, NFORC=16

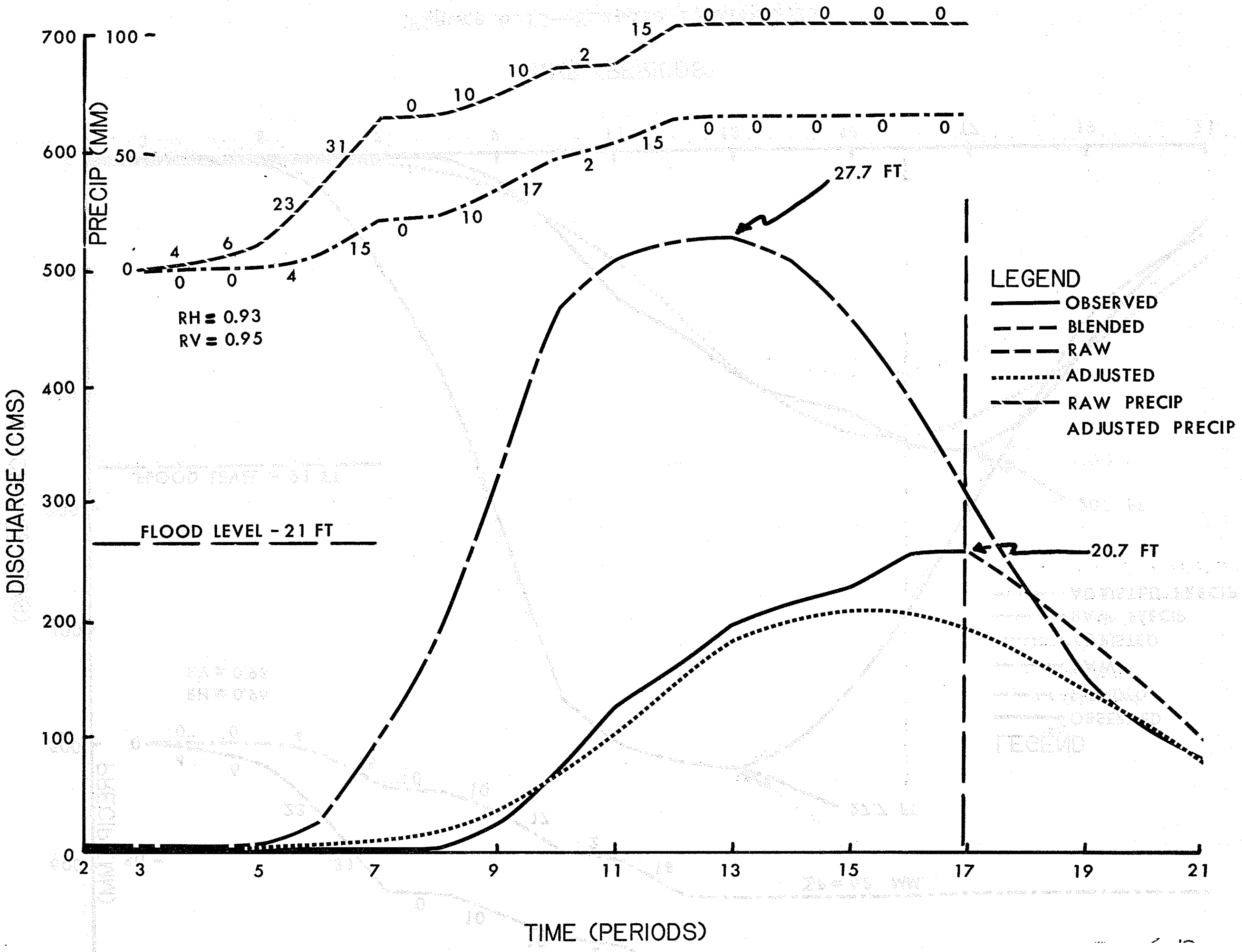


Figure 6.12--Example 1, NFORC=17

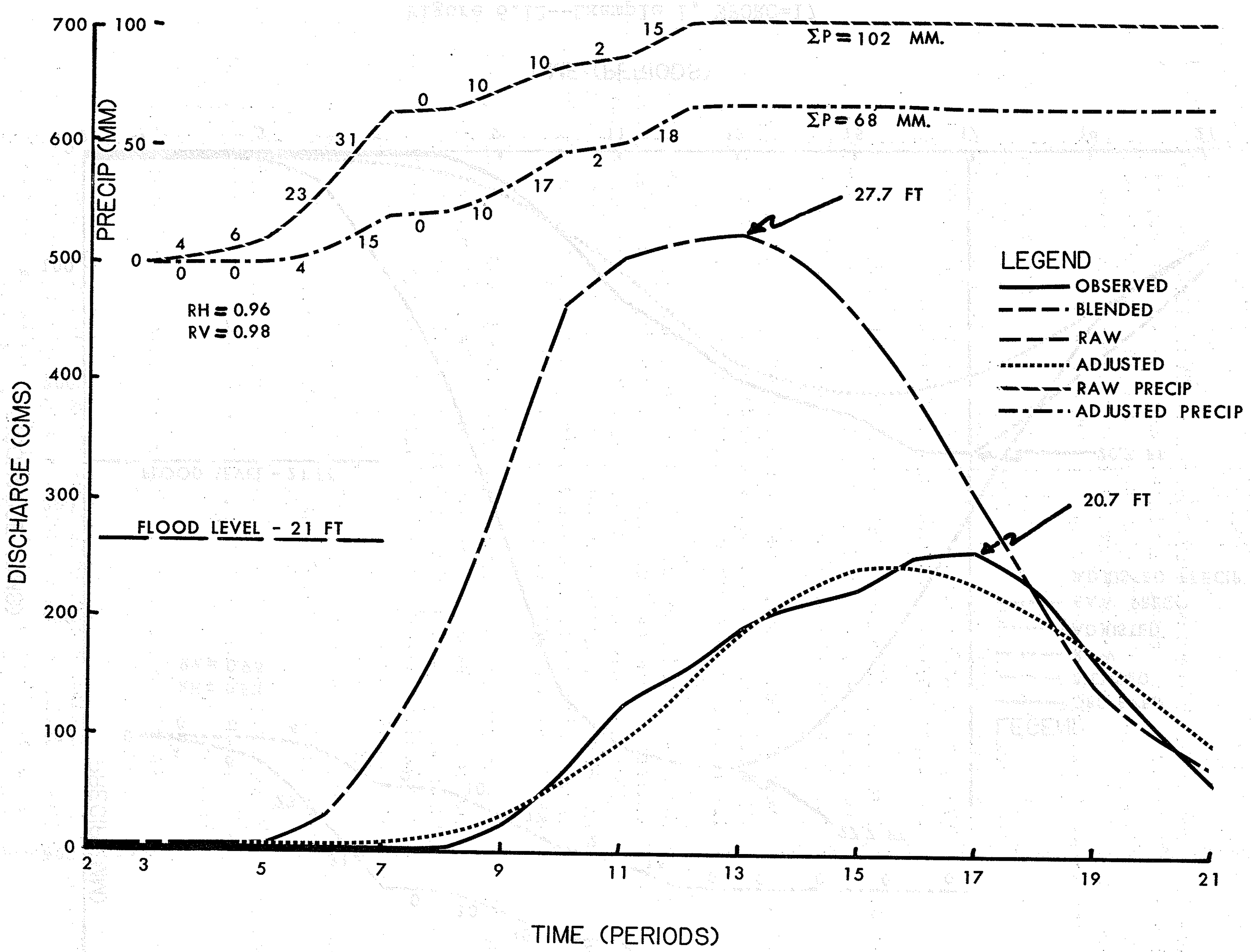


Figure 6.13--Example 1, NFORC=23

Example 2

Example 2 occurred on the Monocacy River near Frederick, Maryland, on June 19-23, 1958. Even though it is a double-peaked event, it is treated as a single runoff event in this example. In an effort to shed some light on what constitutes a runoff event, this same rise is rerun in Example 3 as two separate runoff events.

NFORC 3: After 30 mm of precipitation, both the observations and the raw simulation exhibit slight rises. Since they are in close agreement, CHAT makes no adjustments. It is an insignificant rise, but CHAT does not know this and is, therefore, not influenced by it when making the decision.

NFORC 4: There is a 30-percent disagreement at the latest ordinate, but CHAT does not adjust. Since it is still 12 hours before the forecast peak, this is a reasonable decision.

NFORC 5: The rain has stopped and the observed graph is levelling off. The agreement between the raw simulation and the observations is reasonable and no adjustments are made.

NFORC 6: No more rain has occurred in the past 6 hours but there is a sudden and unexpected rise in the river. CHAT makes upward adjustments to the simulation to agree with the observations. At NFORC 5, there was absolutely no indication that the river might suddenly rise 6 hours later; consequently, the decision CHAT made at NFORC 5 is still logical.

NFORC 7: The observations continue to rise sharply and CHAT increases the precipitation by 5 mm more and alters RH and RV. It concludes that the latest observed is the peak. The raw simulation peaked 6 hours earlier at a stage 2 feet below the latest observation.

NFORC 8: The river is receding at this time, which verifies CHAT's assumption at NFORC 7 concerning the peak.

NFORC 9: After 24 hours, the rain begins again. The simulations forecast another rise, and the additional rainfall justifies such a forecast.

NFORC 10: It is still raining, but the observations are showing no rise.

NFORC 11: The raw simulation indicates that the river should have been rising for the past 18 hours, but the observed is still falling. The adjustments that CHAT makes are minimal even though the agreement during the second rise is not good. CHAT is apparently being influenced by the agreement with the observations during the first rise. This suggests that the procedure might operate in a better manner if the second rise were treated as a separate runoff event.

NFORC 12: The simulation now appears to agree more closely because the observed is finally rising. Even though the results are good at this time period, CHAT, nevertheless, made a bad decision at NFORC 11; the agreement was not acceptable and CHAT should have attempted to improve it.

NFORC 13: The observed is still rising. The adjusted simulation and the observations are almost identical except for a 6-hour displacement in time. However, the idea of treating this example as separate runoff events is still logical.

NFORC 14: The stage of 6 feet at NFORC 13 was the peak and the hydrograph is now in recession.

In summary, the highest stage reached by this event was 6 feet, which is 8 feet below flood stage. The rise was insignificant throughout the entire event, but CHAT was unaware of this and operated in the same manner as it would have on an event of flood proportions. During the early part of the second rise, CHAT's decisions were not good, apparently due to the influence from the first rise. Therefore, it seems advisable to treat this example as two separate runoff events.

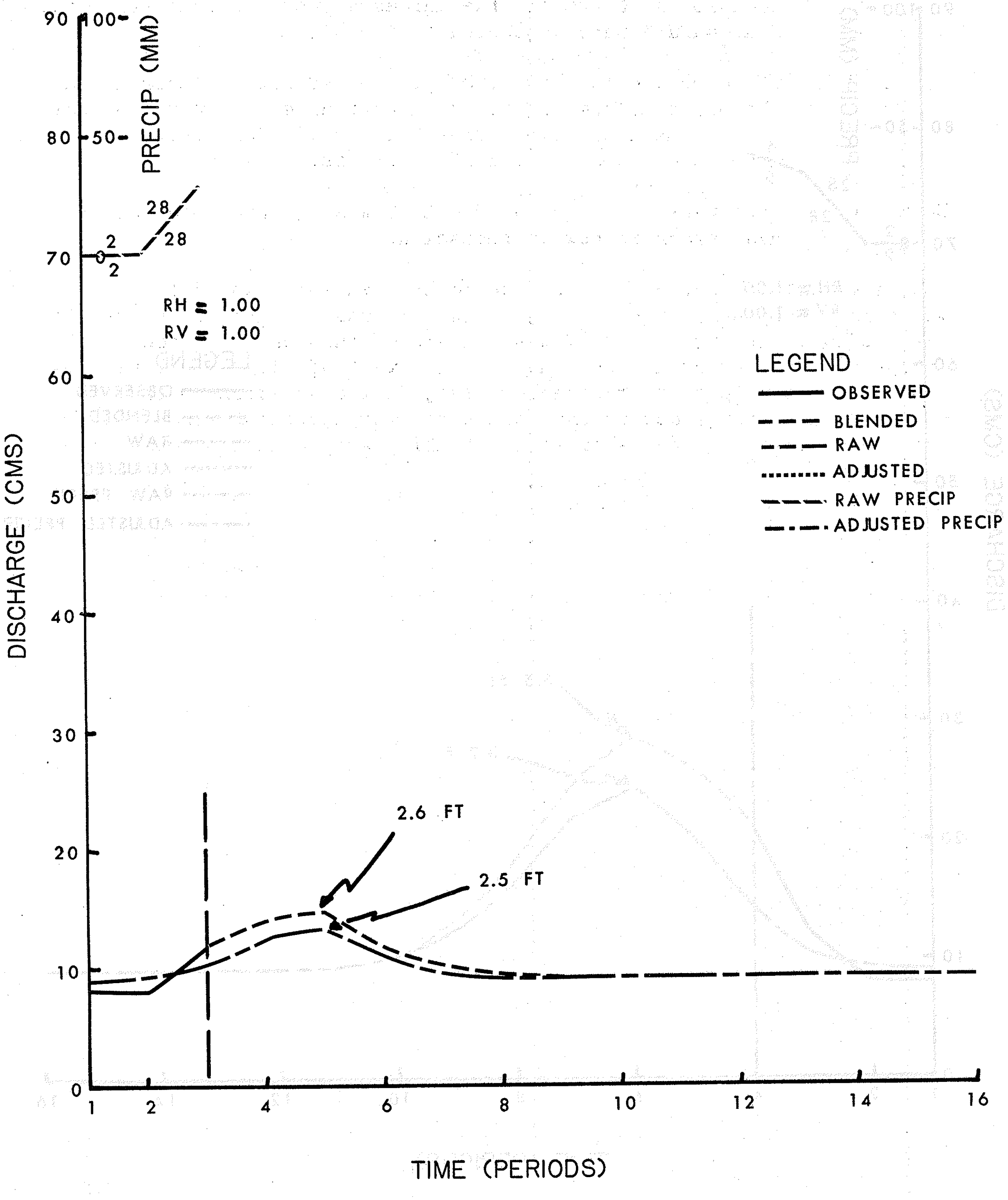


Figure 6.14--Example 2, NFORC=3

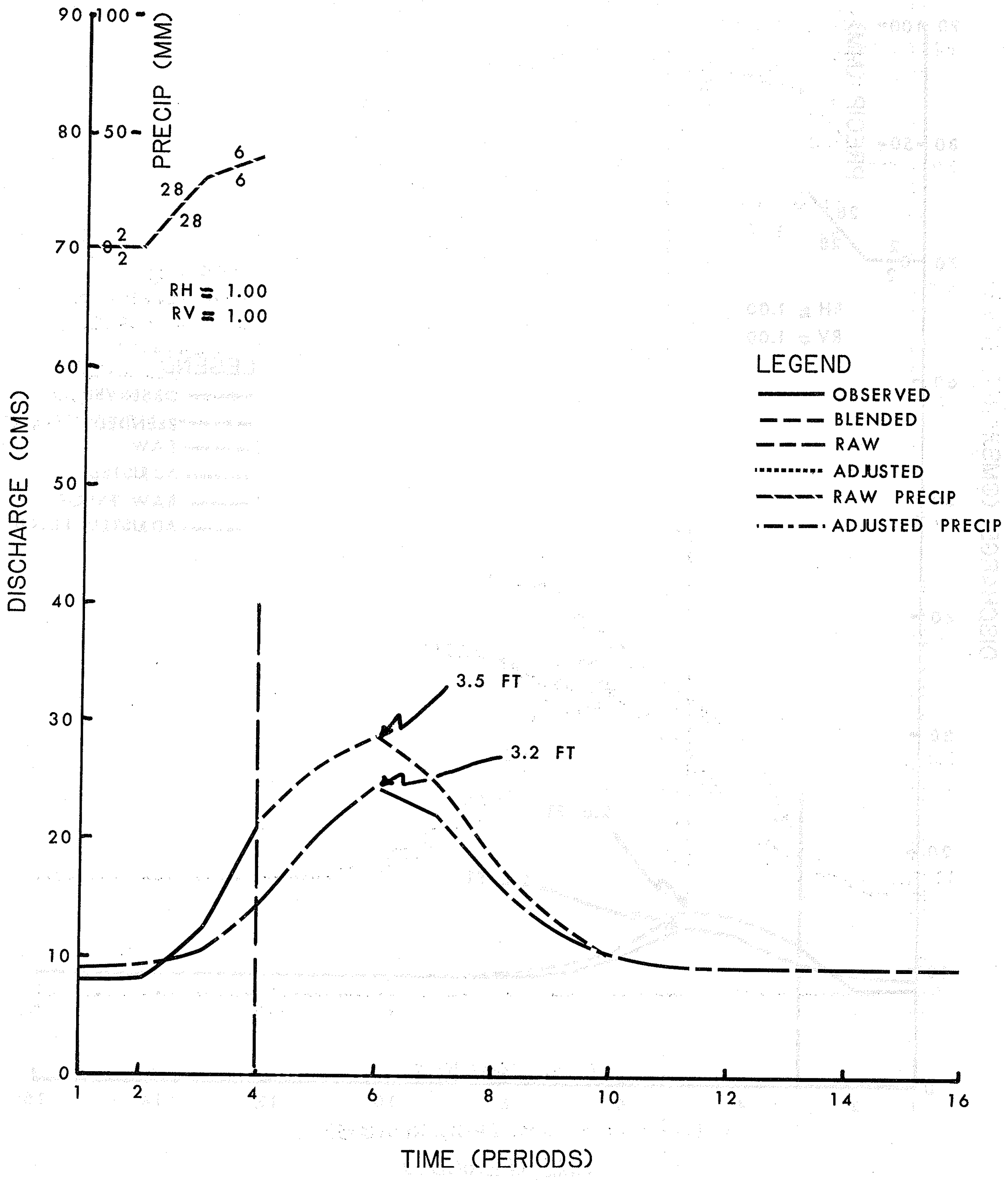


Figure 6.15--Example 2, NFORC=4

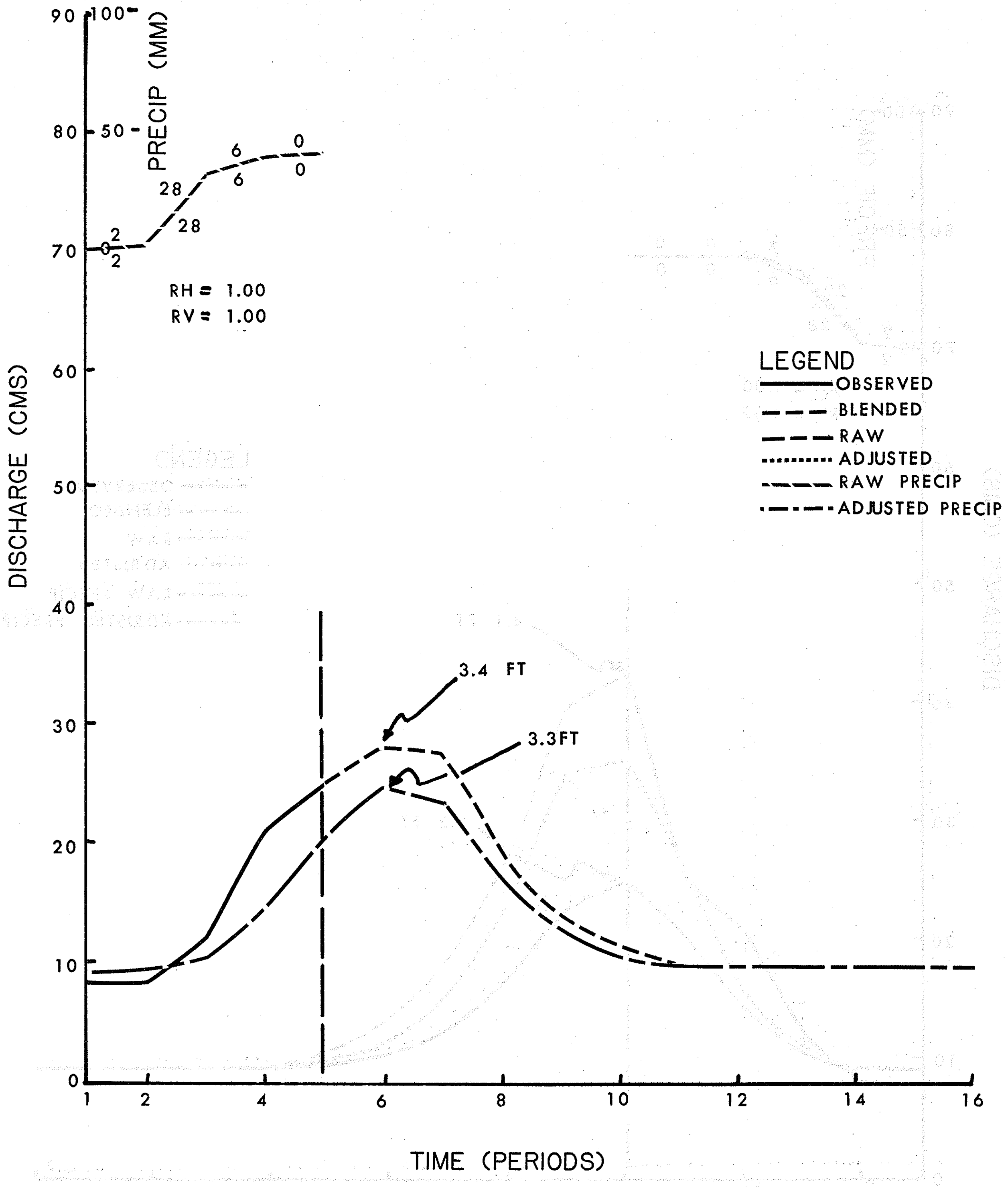


Figure 6.16--Example 2, NFORC=5

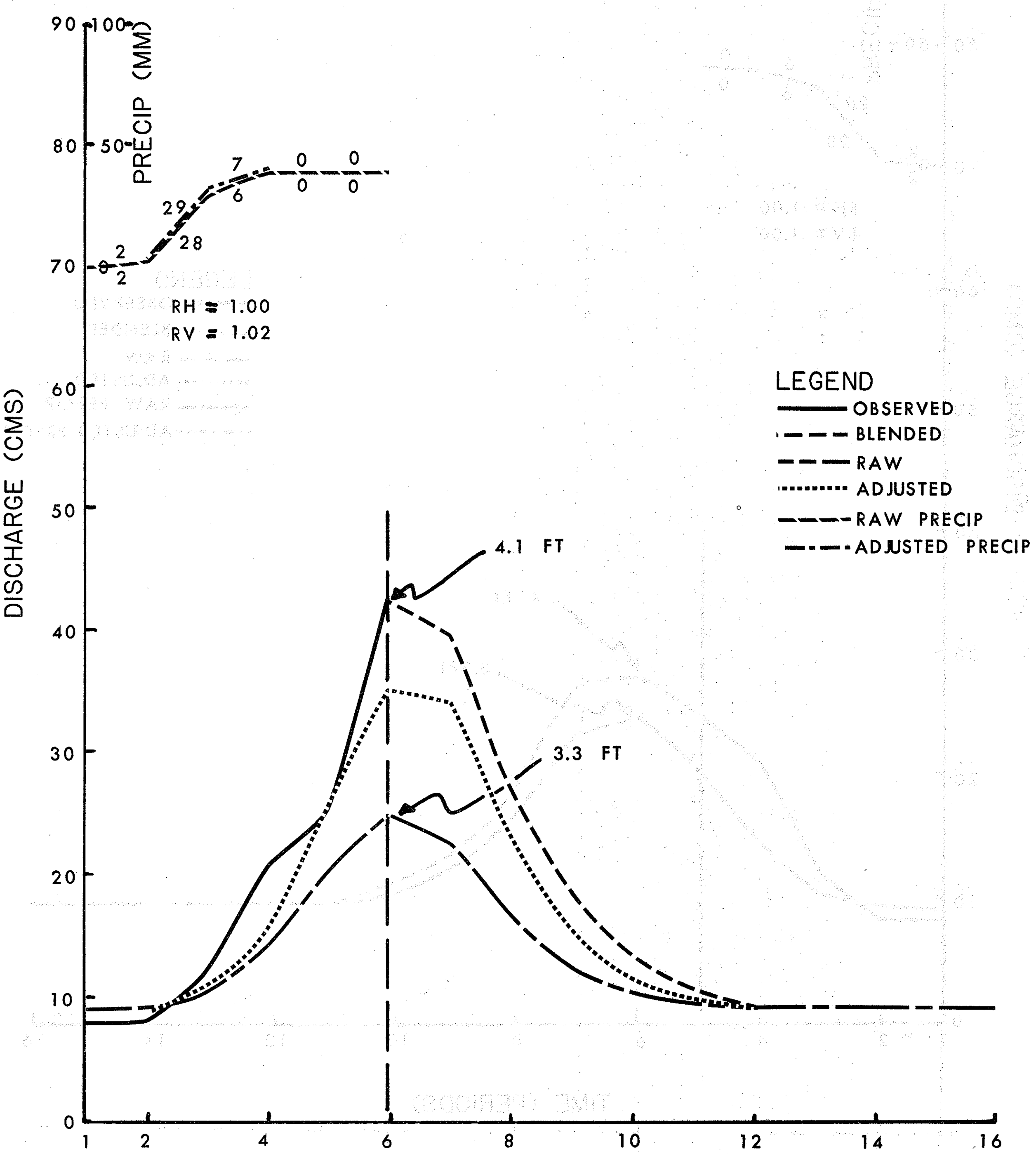


Figure 6.17--Example 2, NFORC=6

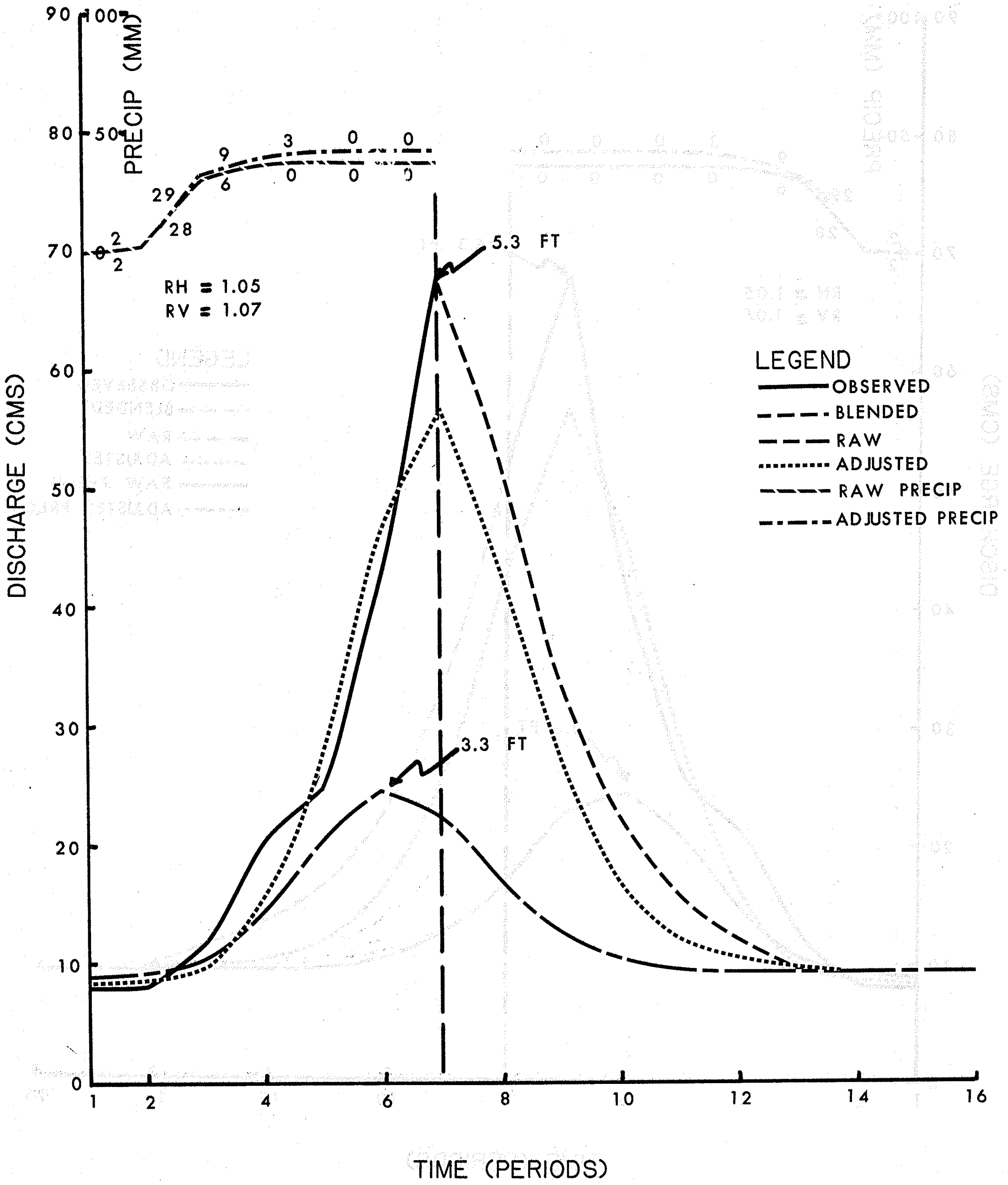


Figure 6.18--Example 2, NFORC=7

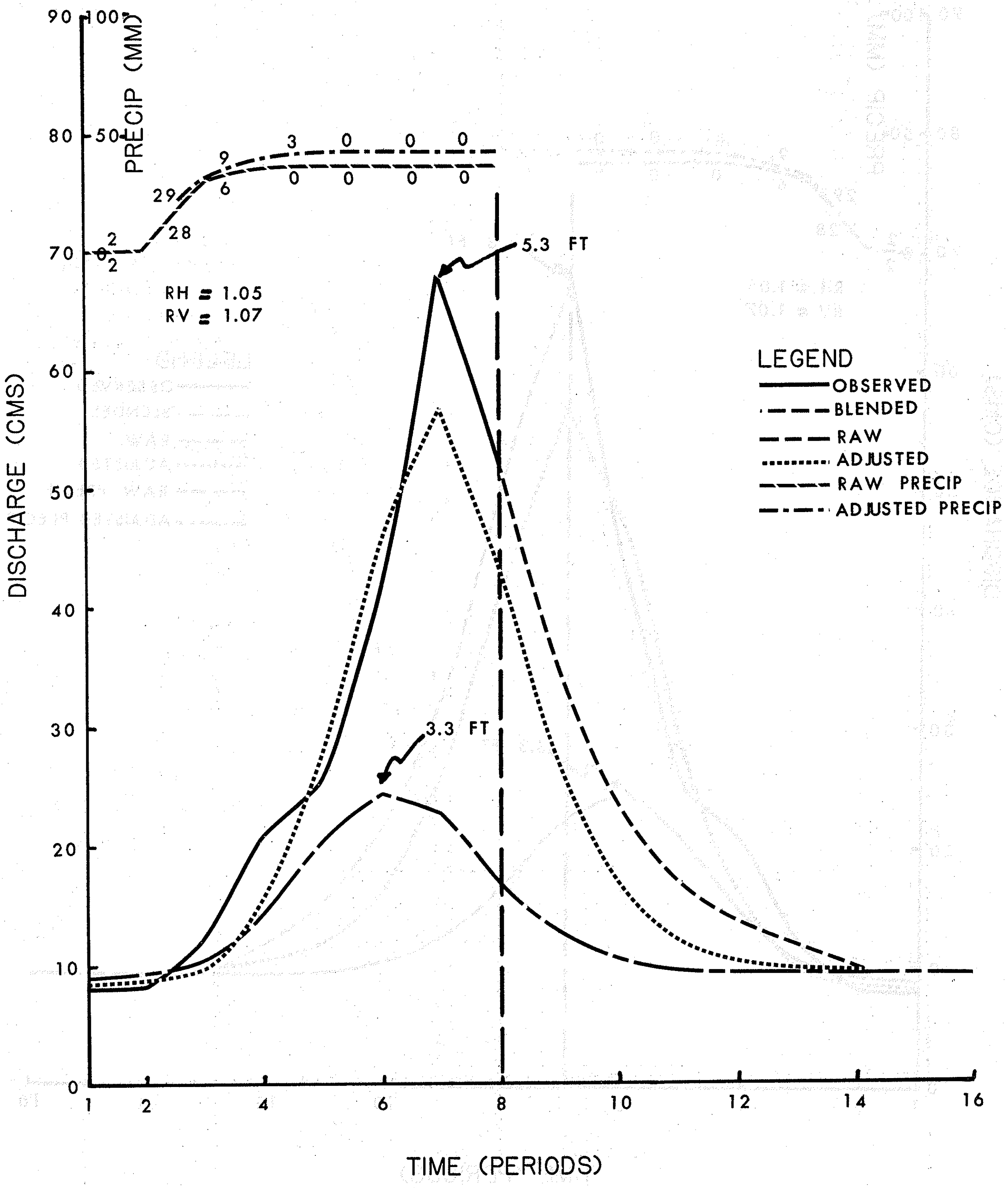


Figure 6.19--Example 2, NFORC=8

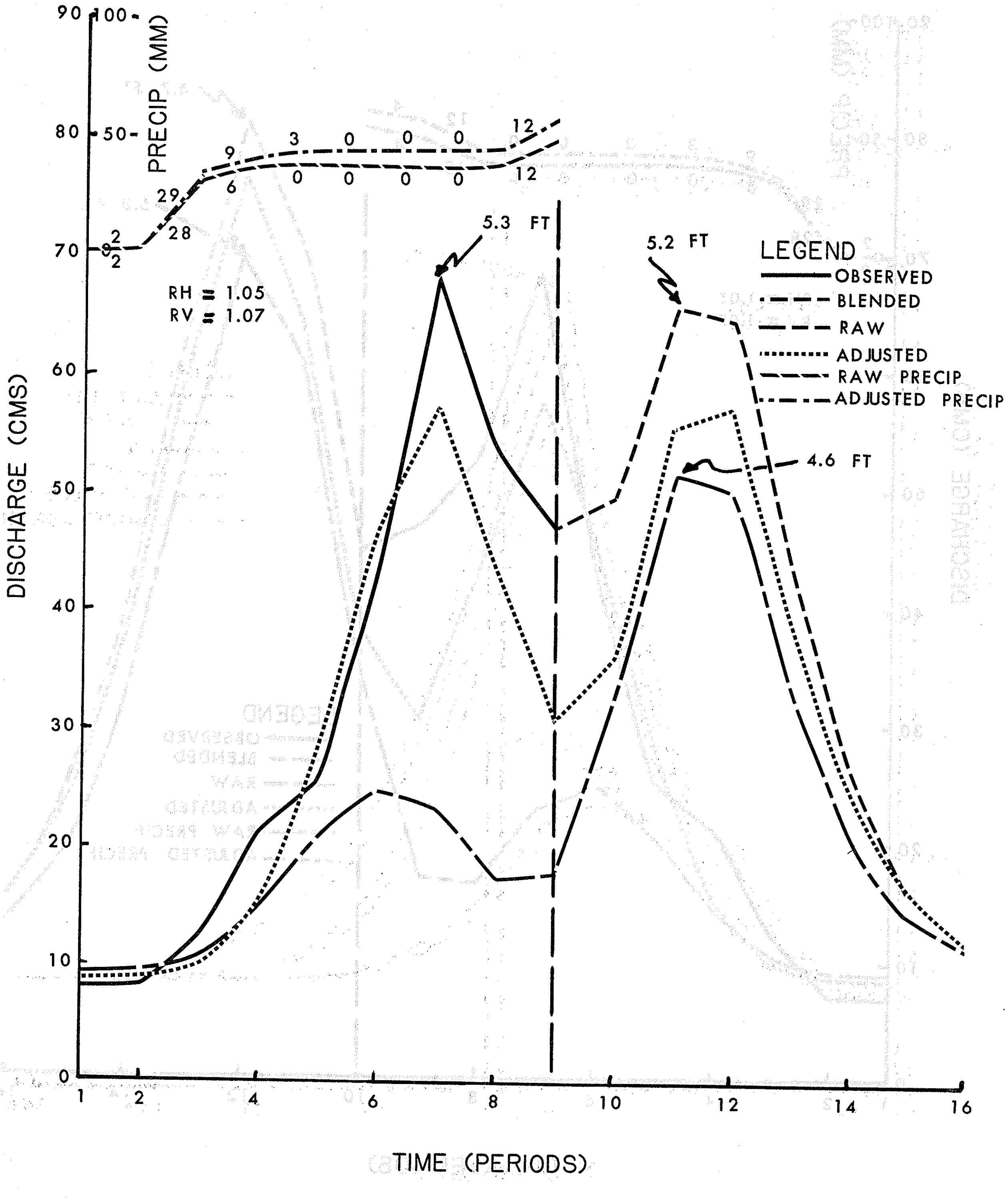


Figure 6.20--Example 2, NFORC=9

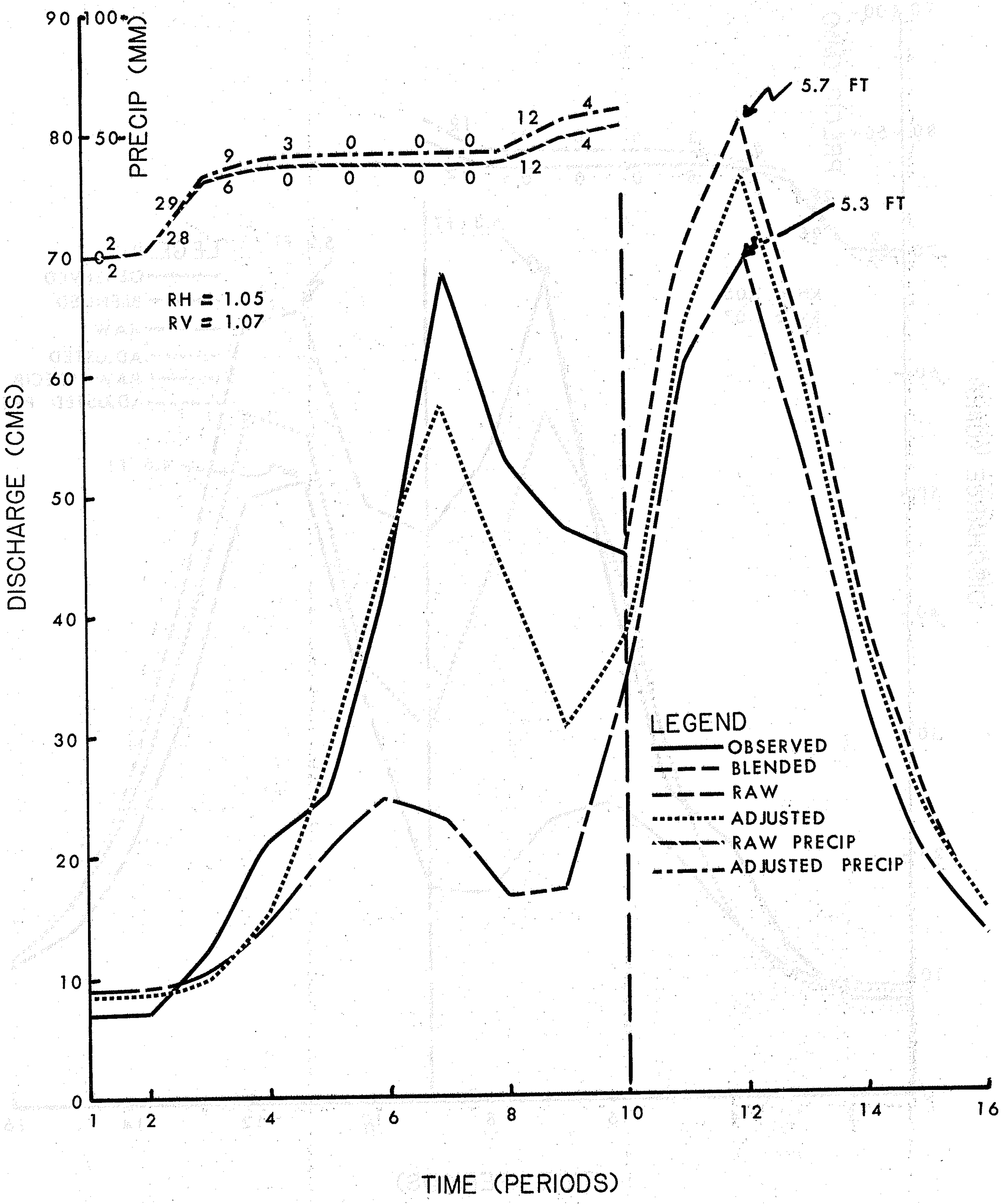


Figure 6.21--Example 2, NFORC=10

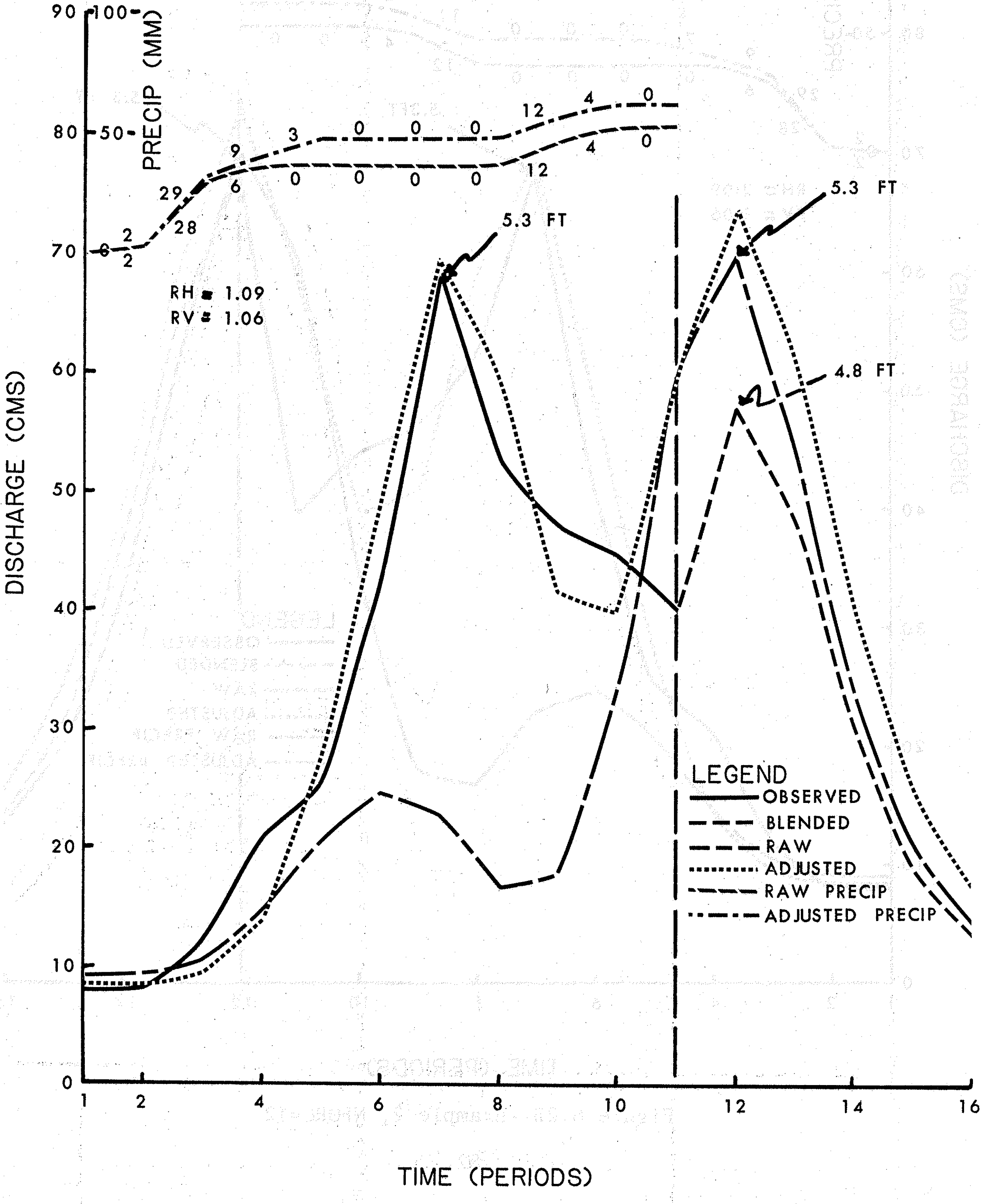


Figure 6.22--Example 2, NFORC=11

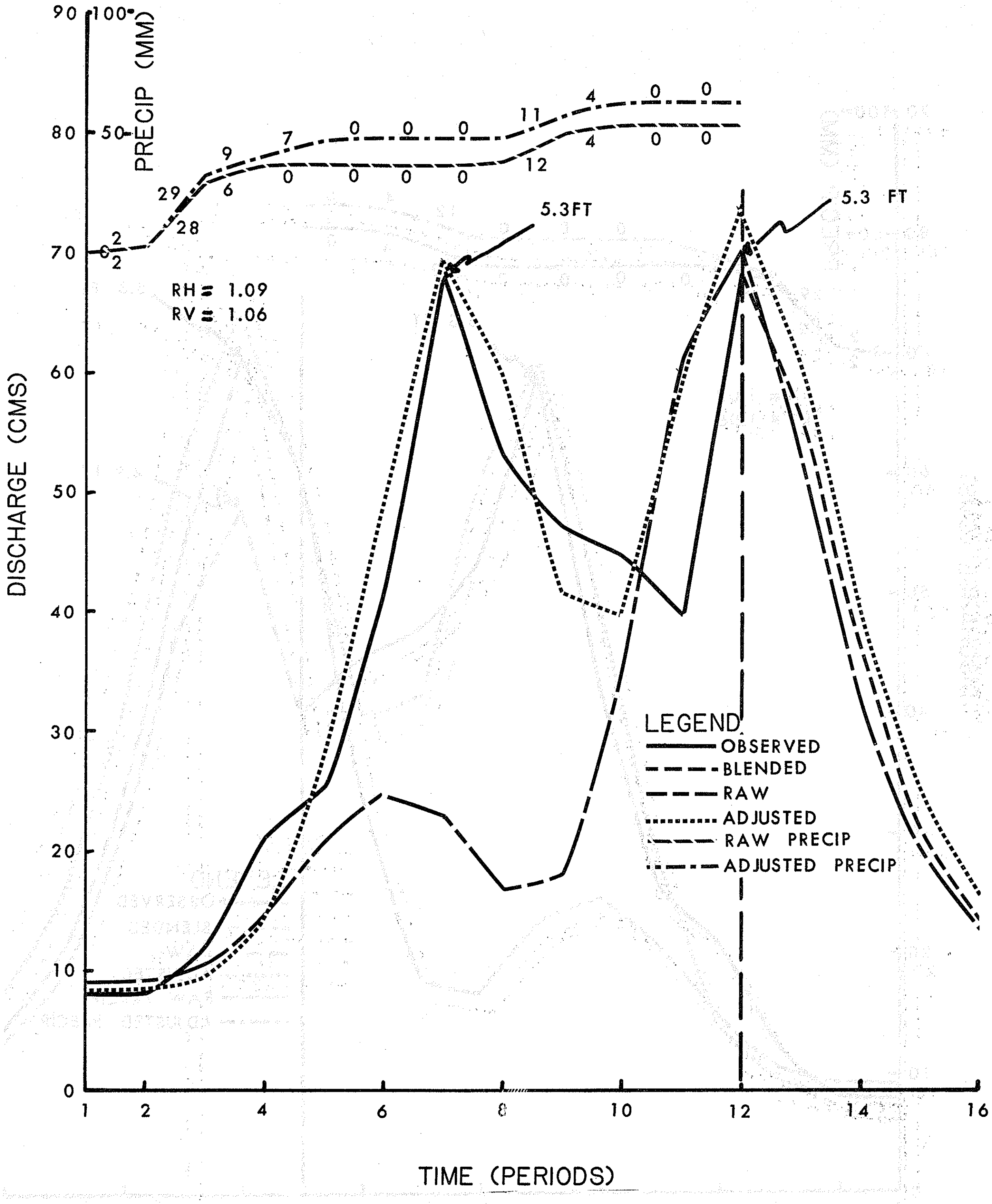


Figure 6.23--Example 2, NFORC=12

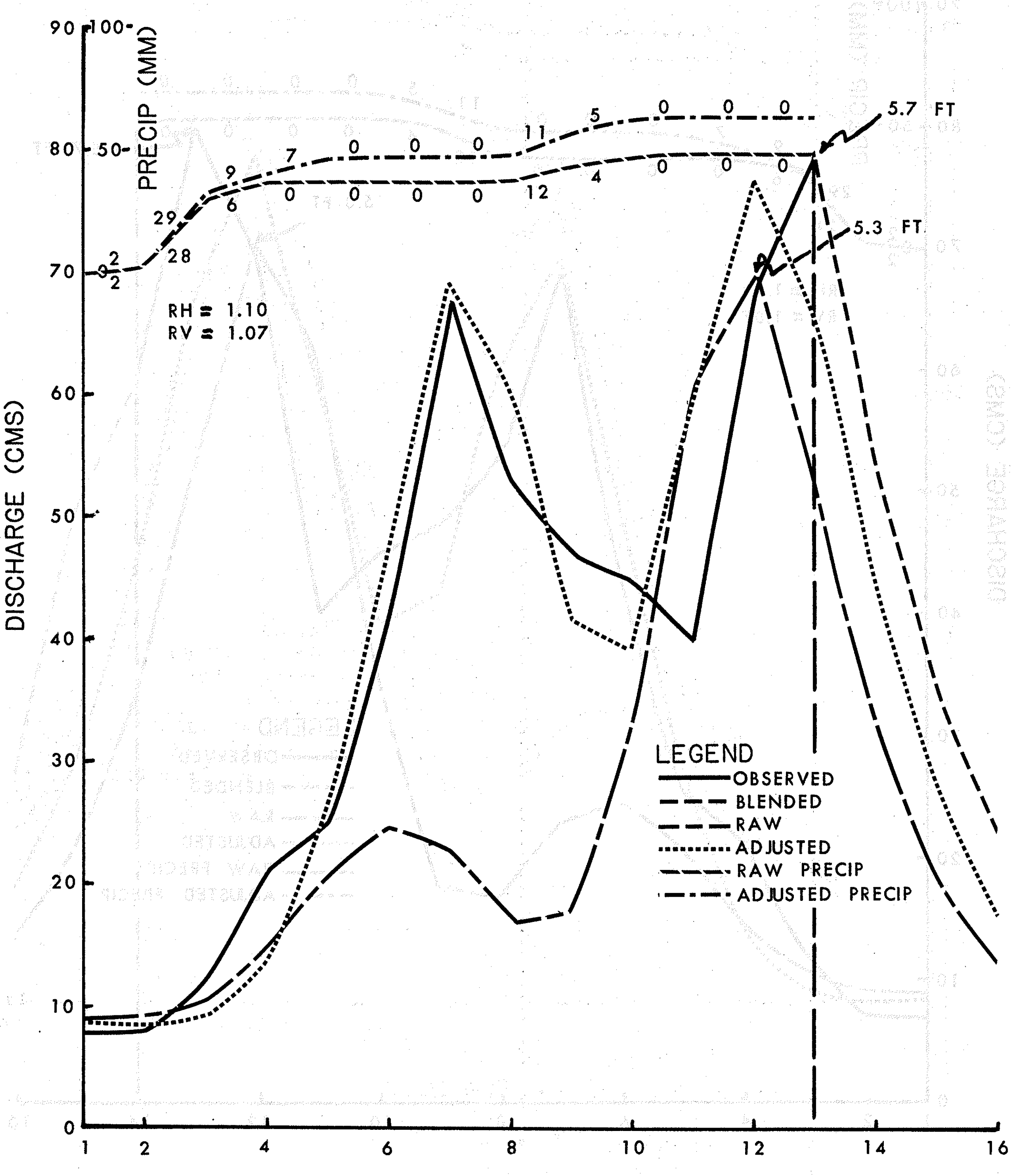


Figure 6.24--Example 2, NFORC=13

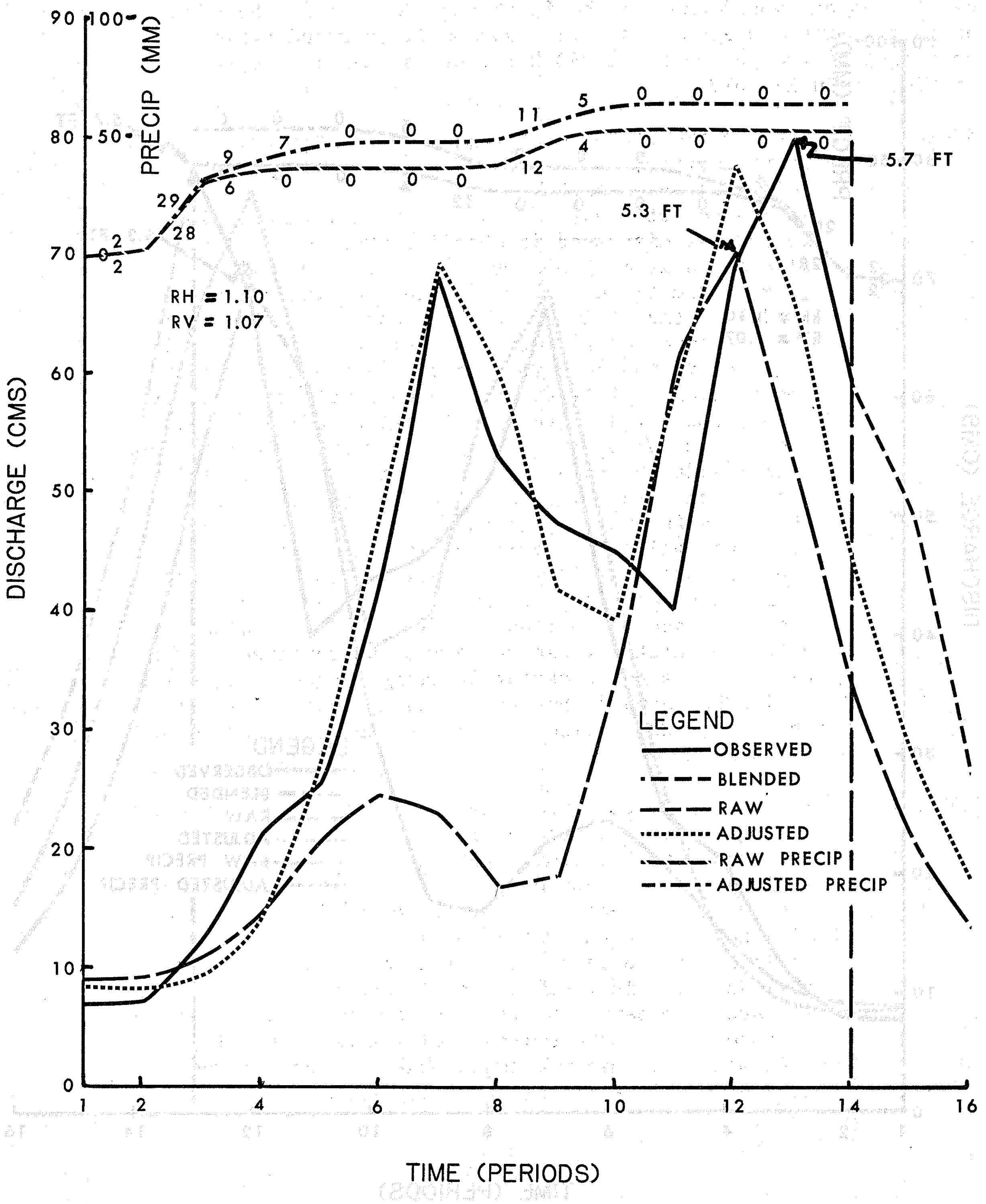


Figure 6.25--Example 2, NFORC=14

Example 3

Example 3 treats the rise of Example 2 as two separate runoff events. As one would expect, the first rise is exactly the same as in the previous example and will not be illustrated again. The beginning of the second rise, NFORC 1 in this example, corresponds to NFORC 8 in Example 2.

NFORC 3: Because the second rise begins on the recession of the previous rise, the first ordinate is the highest at this time. However, CHAT does not treat it as the peak in its computations of MPT for the tolerance. This feature is discussed in detail in Chapter 4. The raw simulation is much higher than what it was in the previous example due to CHAT operating on the first rise, thus rendering the soil-moisture contents much higher at the beginning of this rise. CHAT overreacts and tries to lower it too much to effect an agreement with the observations. This situation would not have occurred with a smaller Δ on the precipitation adjustments. The adjustment on the last pass put the objective function well inside the tolerance. As stated earlier, this adjustment strategy is not intended to minimize the objective function but rather to reduce it to a satisfactory value with as minor modifications to the input as possible. With a smaller Δ the adjustment would have put the objective function just inside the tolerance and not way below it. This Δ size is a CHAT parameter whose value must be supplied by the user. It is not necessarily being suggested that the Δ size be changed, but this example does illustrate the effect the Δ size can have on the performance of the procedure.

NFORC 4: The raw simulation indicates that the river should have been rising for the last 12 hours, more than doubling the discharge in that time. Yet, the observed has been falling steadily during the period. The only logical conclusion is that the simulation should be reduced drastically, which is the course of action CHAT takes. In light of the information available at this time, this decision is logical even if one is "over one's head" in water the next 6 hours. In comparison with Example 2, note that at the corresponding time, NFORC 11, CHAT made only minimal adjustments because it was taking into account the fit of the first rise as well.

NFORC 5: The hydrograph is now rising. CHAT responds by adding 6 mm of precipitation, thereby increasing the peak. Note that at this point the adjusted precipitation totals 15 mm - the same as in Example 2. Now that the river is finally rising, both examples are behaving similarly. Prior to the rise, however, they were operating quite differently. In comparison, CHAT in Example 2 made a bad decision at NFORC 11 but was fortunate in that the results were good at NFORC 12: at the corresponding periods in Example 3, its decision at NFORC 4 was logical even though the results were poor at NFORC 5.

NFORC 6-7: CHAT makes only minor adjustments from this point on through to the end of the event. The major point has already been illustrated at periods 4 and 5.

In summary it is felt that the decisions made in this example were more logical decisions than those made at the corresponding periods in Example 2, even though the results were not as good. Since CHAT must be evaluated on the basis of the rationality of its decisions rather than the outcome of the decisions, the conclusion is inescapable: the CHAT procedure does what it is supposed to do better when the two rises are treated separately than when they are treated as one runoff event.

The usage of the CHAT procedure requires the identification of the beginning and the end of the runoff event. It is hoped that this example has provided some insight into the problem of defining runoff events. It is an age-old problem for the forecaster and no attempt has been made to solve it in this study.

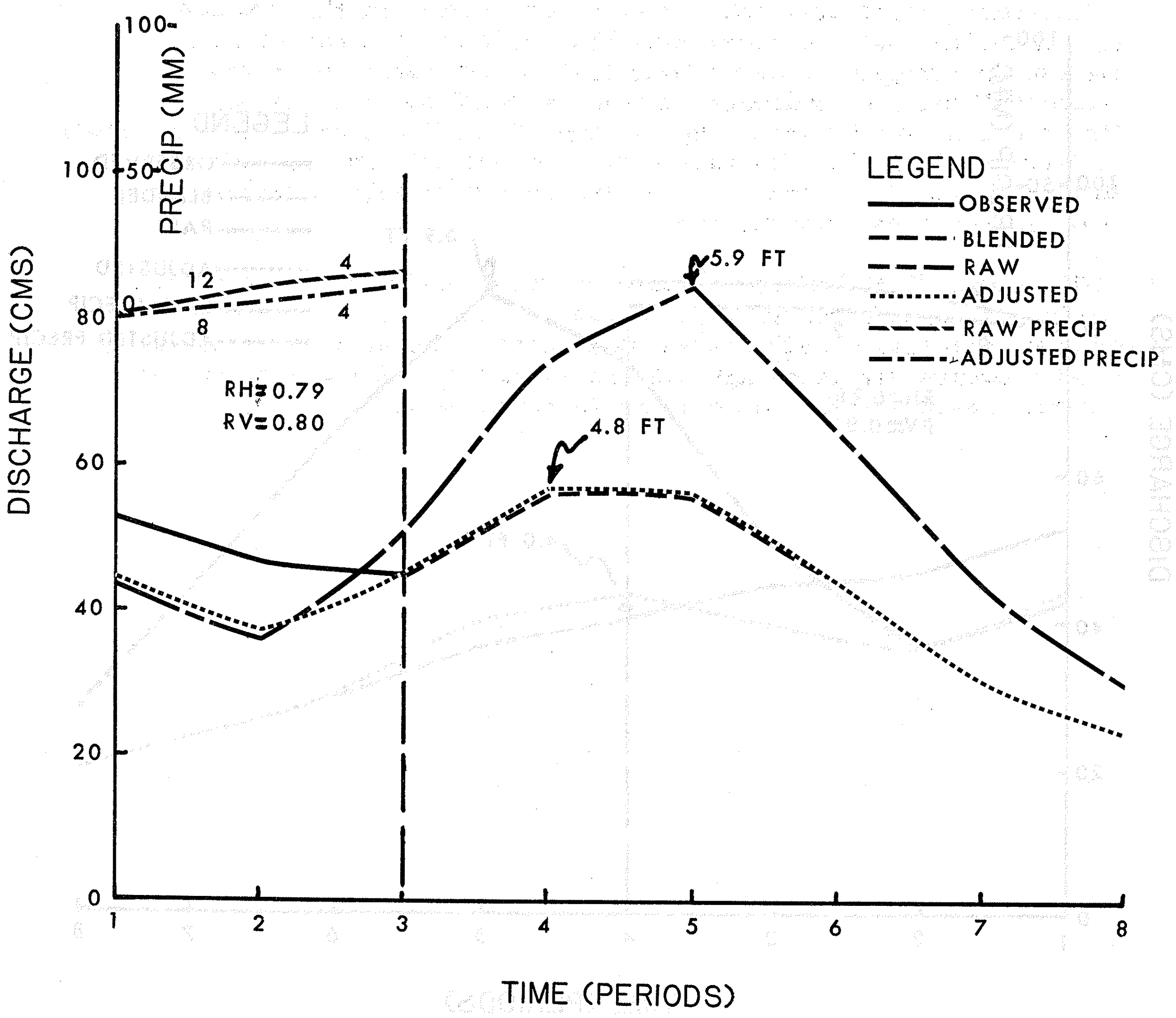


Figure 6.26--Example 3, NFORC=3

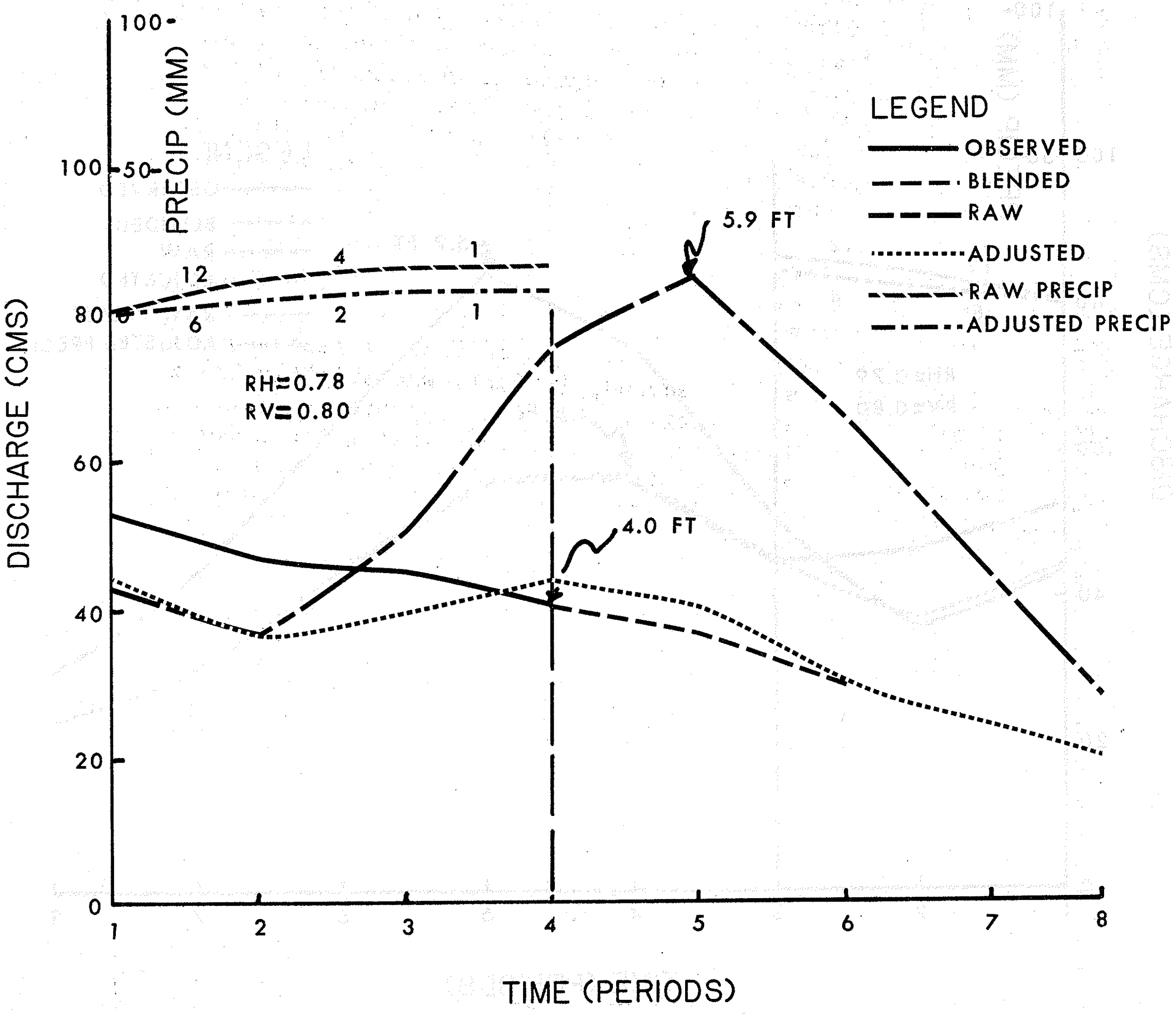


Figure 6.27--Example 3, NFORC=4

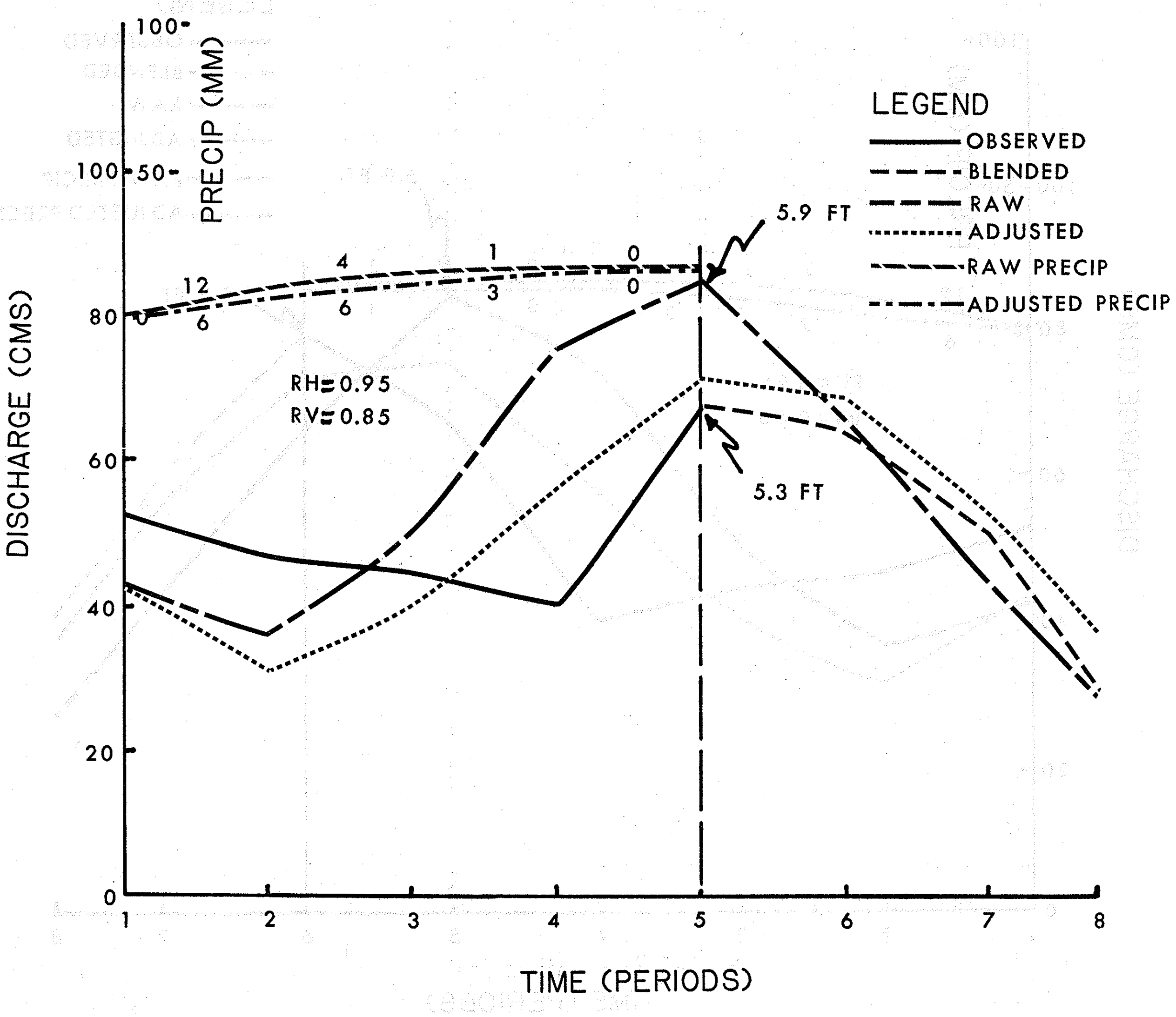


Figure 6.28--Example 3, NFORC=5

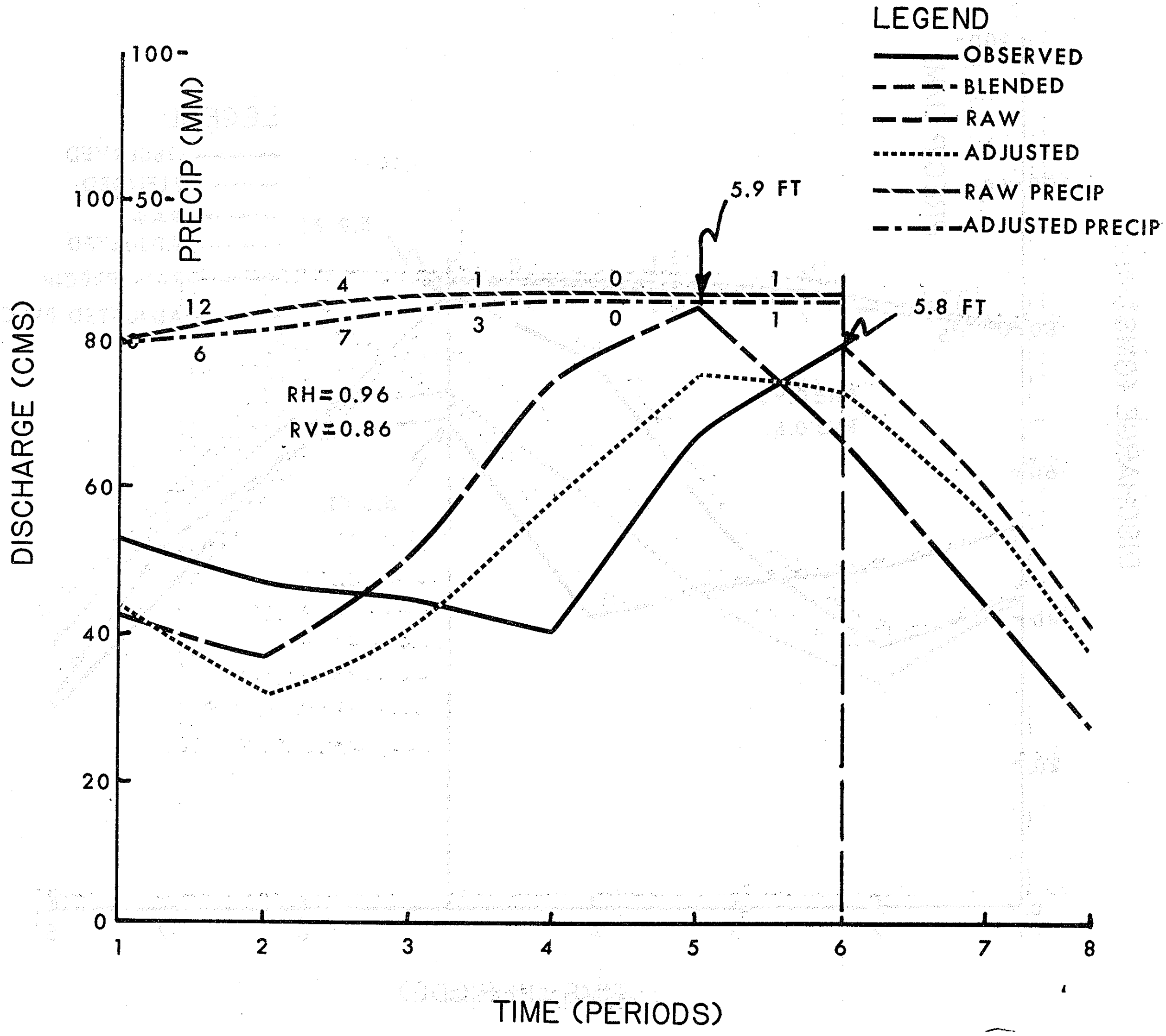


Figure 6.29--Example 3, NFORC=6

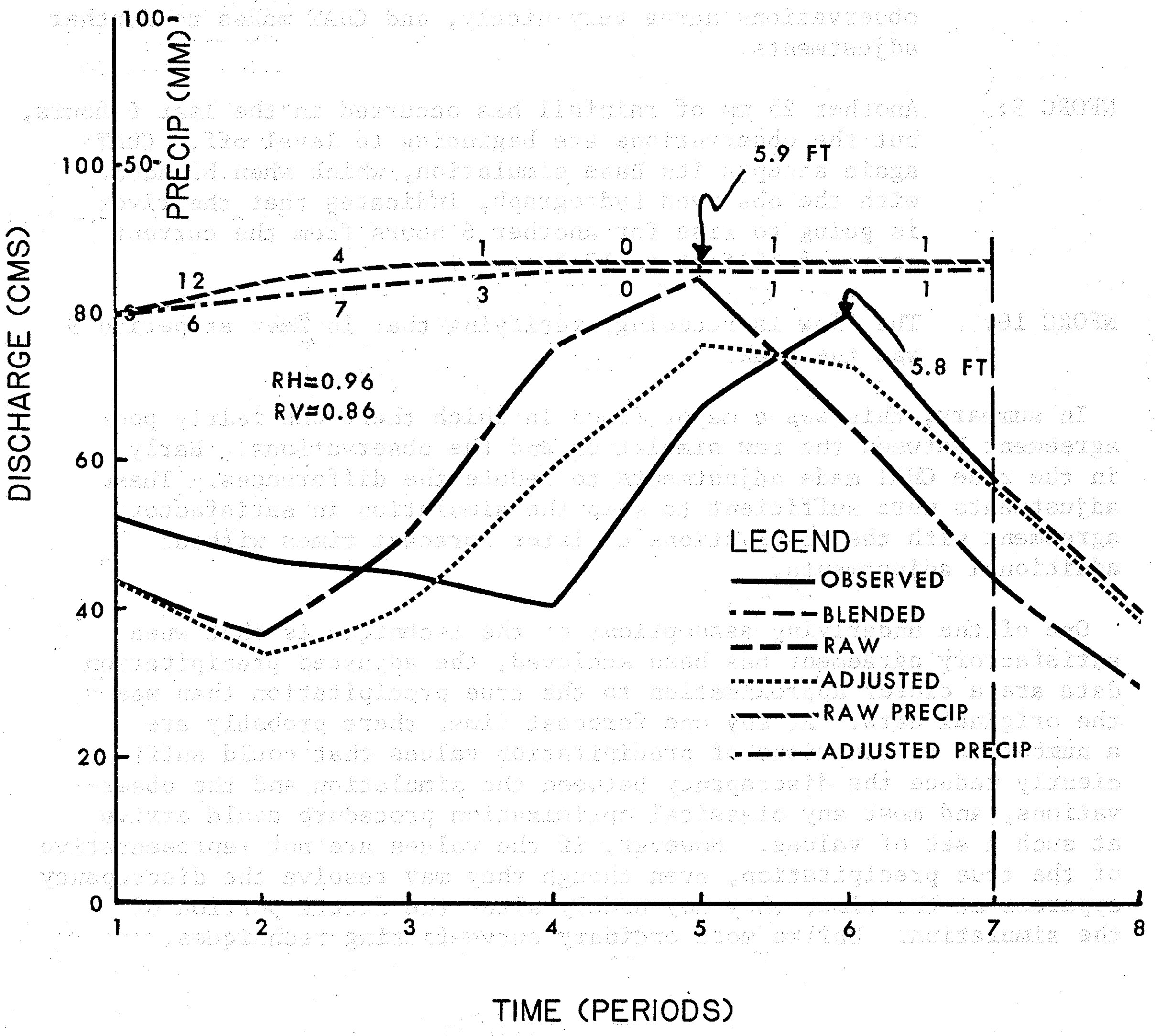


Figure 6.30--Example 3, NFORC=7

Example 4

Example 4 is a rise that occurred on the Monocacy River near Frederick, Maryland, on August 11, 1955. This storm, better remembered as hurricane "Connie," produced a major flood as this example illustrates.

NFORC 7:	After an insignificant rise at the very beginning, the observed hydrograph is now rising sharply. The raw simulation is much lower and rising less steeply. CHAT revises the hydrograph upward and earlier - a perfectly logical adjustment at this time.
NFORC 8:	There is an additional 28 mm of precipitation. The river is at flood stage, 14 feet, and is rising rapidly. The raw simulation is very low. As a result of CHAT's adjustments at period 7, the base hydrograph and the observations agree very nicely, and CHAT makes no further adjustments.
NFORC 9:	Another 25 mm of rainfall has occurred in the last 6 hours, but the observations are beginning to level off. CHAT again accepts its base simulation, which when blended with the observed hydrograph, indicates that the river is going to rise for another 6 hours from the current stage of 16 feet to 17 feet.
NFORC 10:	The flow is receding, verifying that 16 feet at period 9 was the peak.

In summary, this was a major flood in which there was fairly poor agreement between the raw simulation and the observations. Early in the rise CHAT made adjustments to reduce the differences. These adjustments were sufficient to keep the simulation in satisfactory agreement with the observations at later forecast times without additional adjustments.

One of the underlying assumptions of the technique is that when satisfactory agreement has been achieved, the adjusted precipitation data are a closer approximation to the true precipitation than was the original data. At any one forecast time, there probably are a number of combinations of precipitation values that could sufficiently reduce the discrepancy between the simulation and the observations, and most any classical optimization procedure could arrive at such a set of values. However, if the values are not representative of the true precipitation, even though they may resolve the discrepancy apparent at the time, they may unduly alter the future portion of the simulation. Unlike most ordinary curve-fitting techniques, the CHAT adjustment strategy is designed to account for the physical significance of the decision variables, thereby increasing the likelihood of finding a set of adjusted values that are truly a closer approximation to the actual precipitation. At the same time, it can resolve the difference between the simulation and the observations without unjustified modifications to the future portion of the hydrograph.

For the most part, the examples are evidence that the CHAT procedure is behaving in this manner. Adjustments to each precipitation amount are not fluctutating widely from one forecast time to the next as they quite possibly would if the procedure were simply curve fitting. Oftentimes, as in this example, a few adjustments early in the rise resolve the current disagreement and also produce a future simulation that agrees with the observations at later forecast times without further adjustments. This kind of result is possible only if the adjustments are indeed producing a data set that better represents the true precipitation.

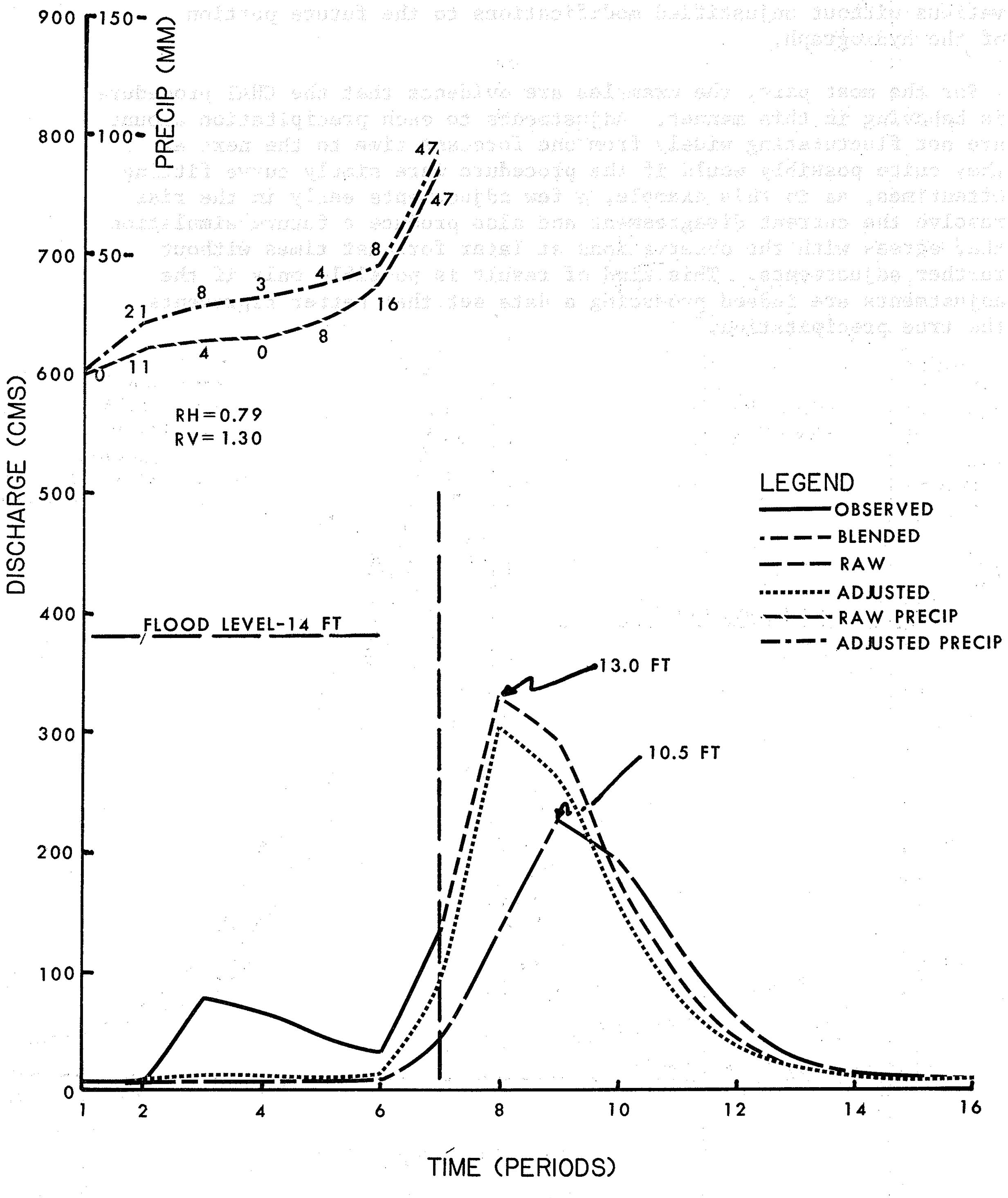


Figure 6.31--Example 4, NFORC=7

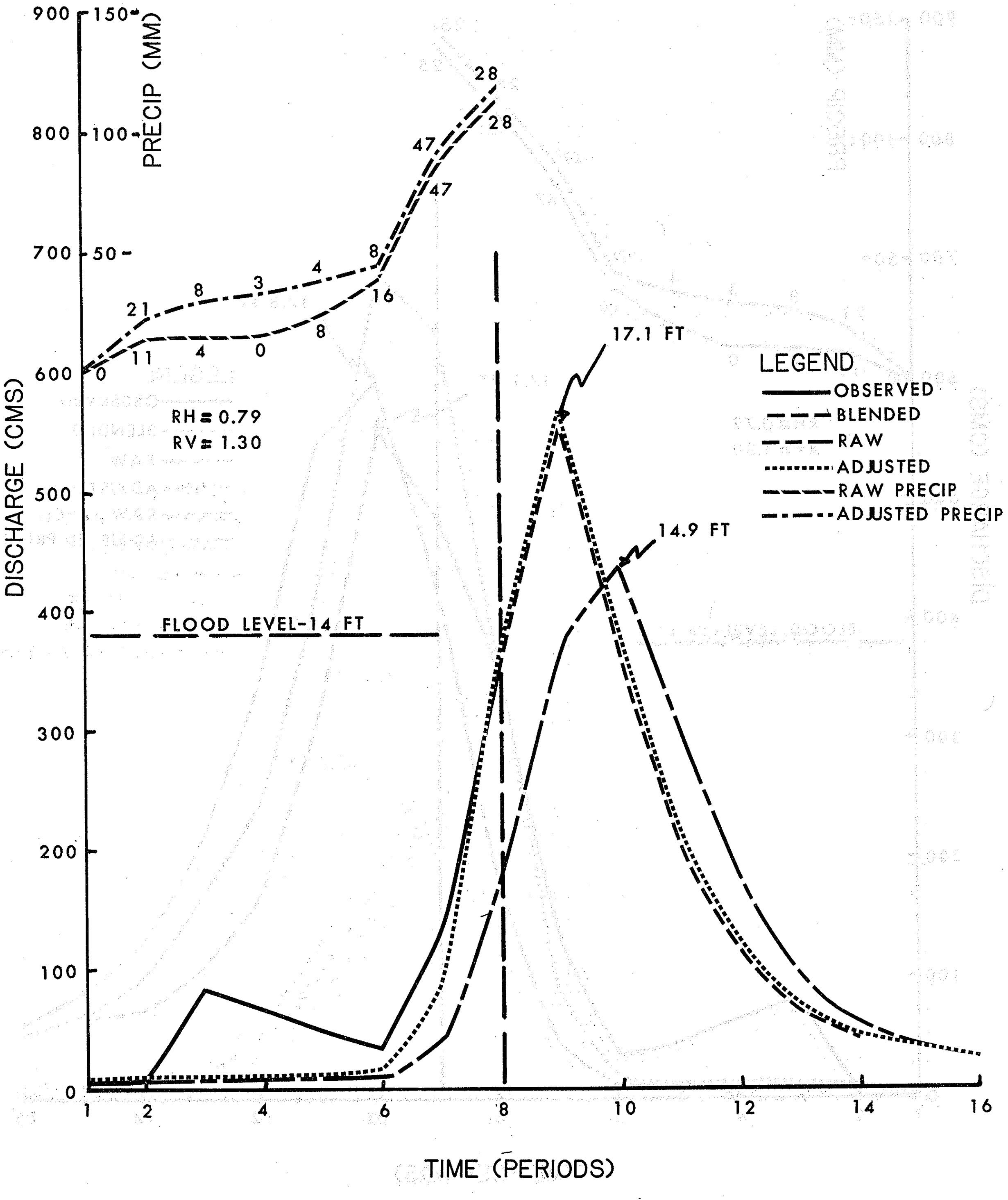


Figure 6.32--Example 4, NFORC=8

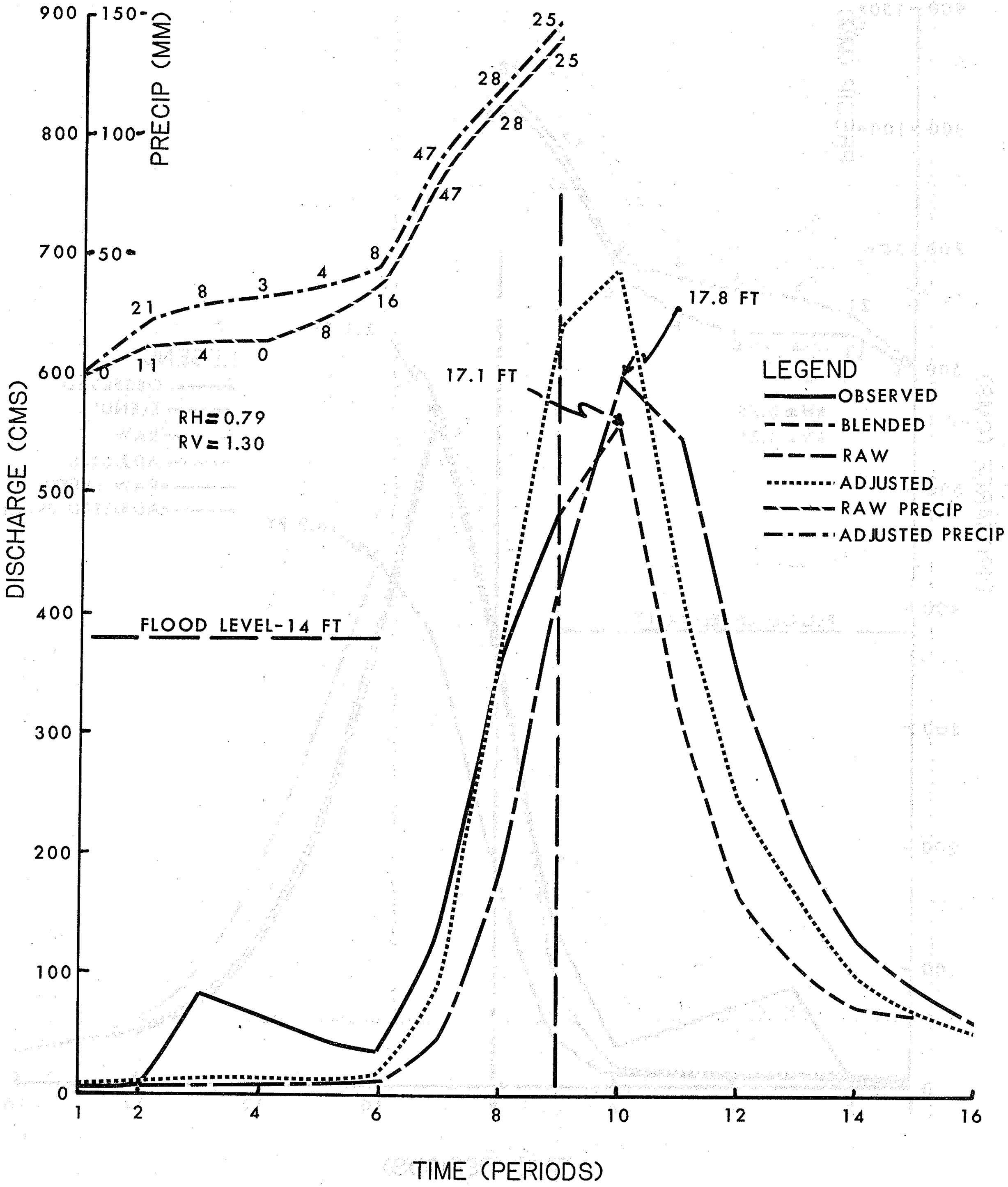


Figure 6.33--Example 4, NFORC=9

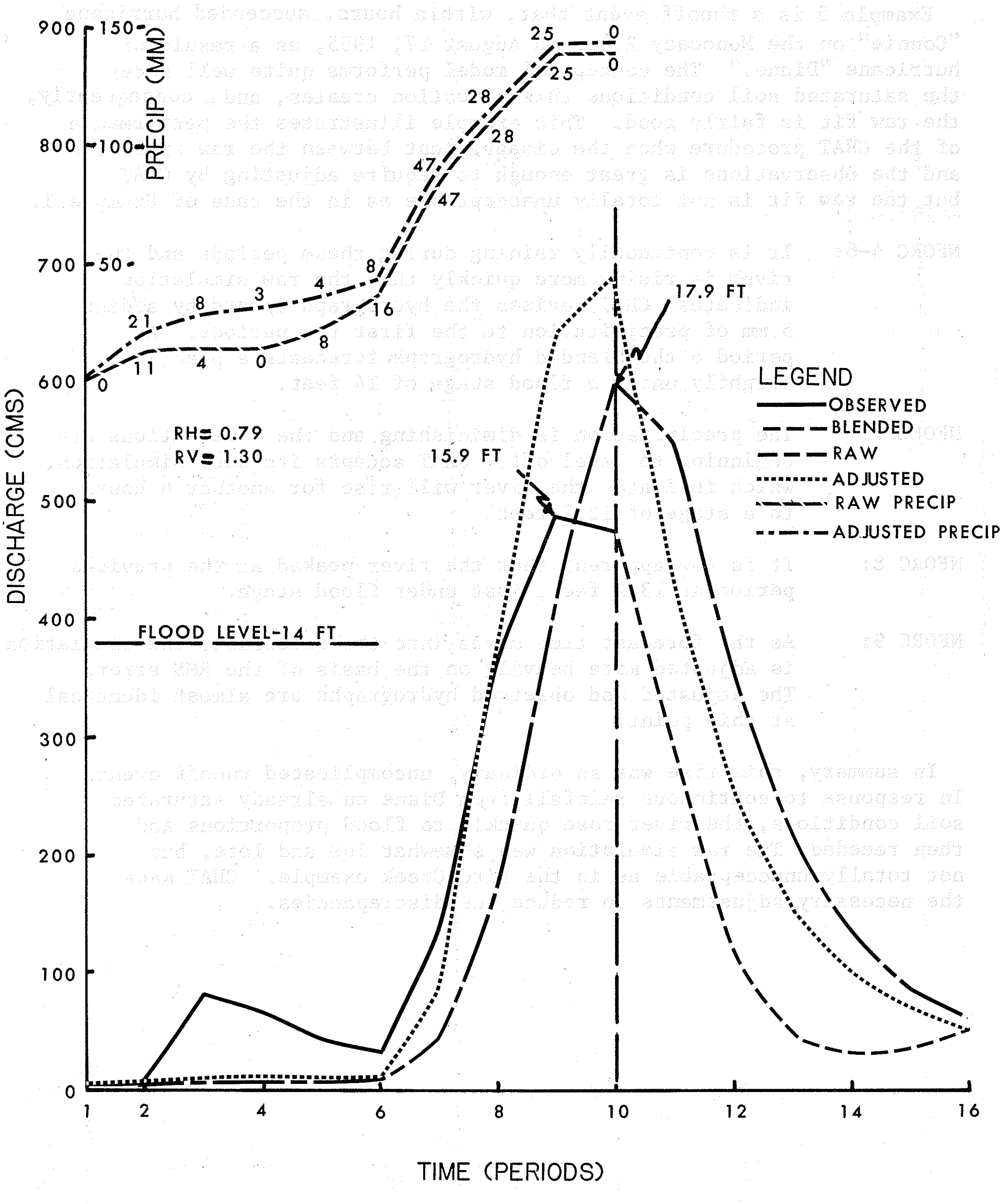


Figure 6.34--Example 4, NFORC=10

Example 5

Example 5 is s runoff event that, within hours, succeeded hurricane "Connie" on the Monocacy River on August 17, 1955, as a result of hurricane "Diane." The conceptual model performs quite well under the saturated soil conditions this situation creates, and, consequently, the raw fit is fairly good. This example illustrates the performance of the CHAT procedure when the disagreement between the raw simulation and the observations is great enough to require adjusting by CHAT, but the raw fit is not totally unacceptable as in the case of Example 1.

NFORC 4-6:	It is continually raining during these periods and the river is rising more quickly than the raw simulation indicates. CHAT revises the hydrograph upward by adding 5 mm of precipitation to the first two periods. At period 6 the blended hydrograph forecasts a peak just slightly under a flood stage of 14 feet.
NFORC 7:	The precipitation is diminishing and the observations are beginning to level off. CHAT accepts its base simulation, which indicates the river will rise for another 6 hours to a stage of 13.5 feet.
NFORC 8:	It is now apparent that the river peaked at the previous period at 13.2 feet, just under flood stage.
NFORC 9:	As the forecast time moves into the recession, the simulation is adjusted more heavily on the basis of the RMS error. The adjusted and observed hydrographs are almost identical at this point.

In summary, this rise was an ordinary, uncomplicated runoff event. In response to continuous rainfall from Diane on already saturated soil conditions, the river rose quickly to flood proportions and then receded. The raw simulation was somewhat low and late, but not totally unacceptable as in the Bird Creek example. CHAT made the necessary adjustments to reduce the discrepancies.

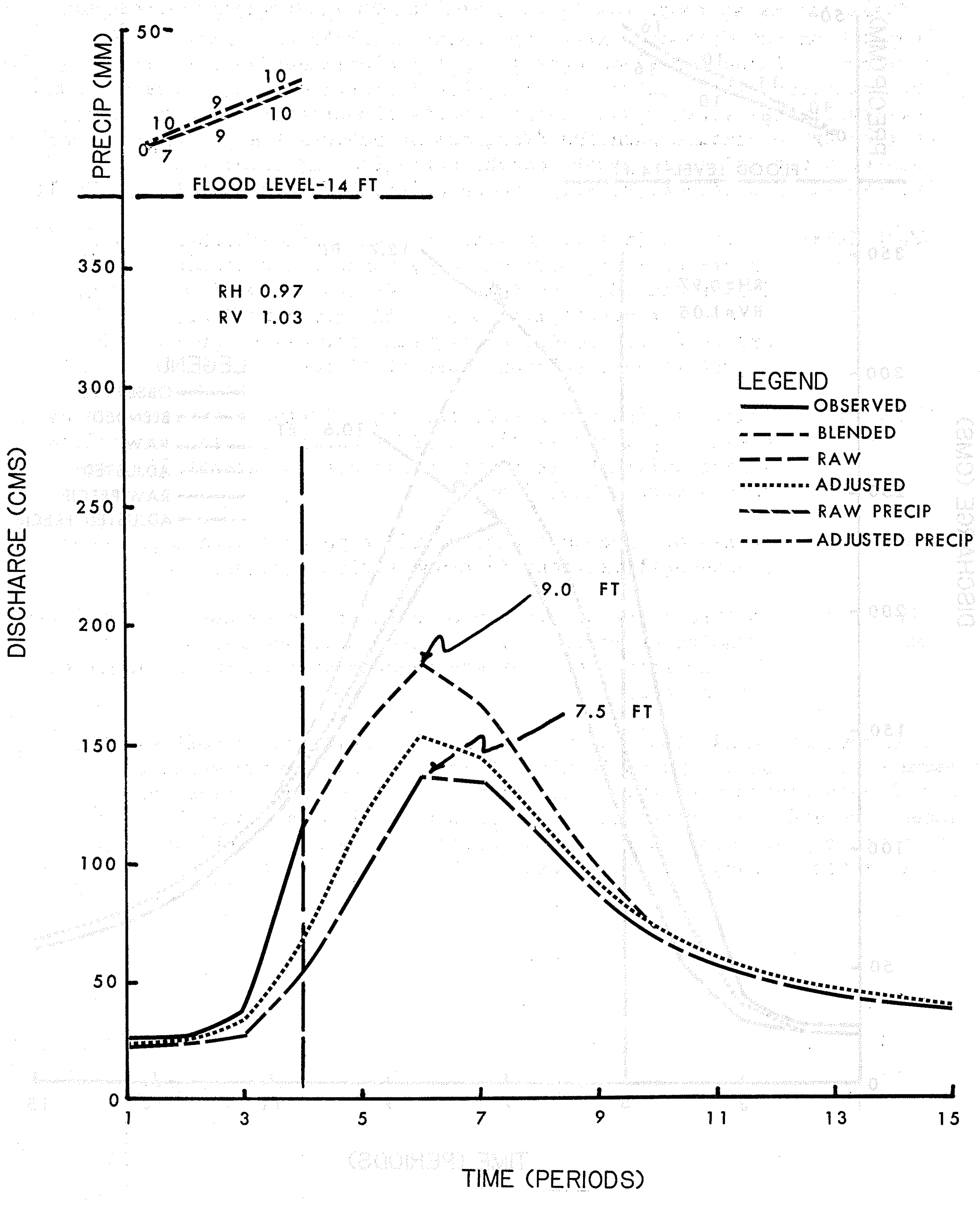


Figure 6.35--Example 5, NFORC=4

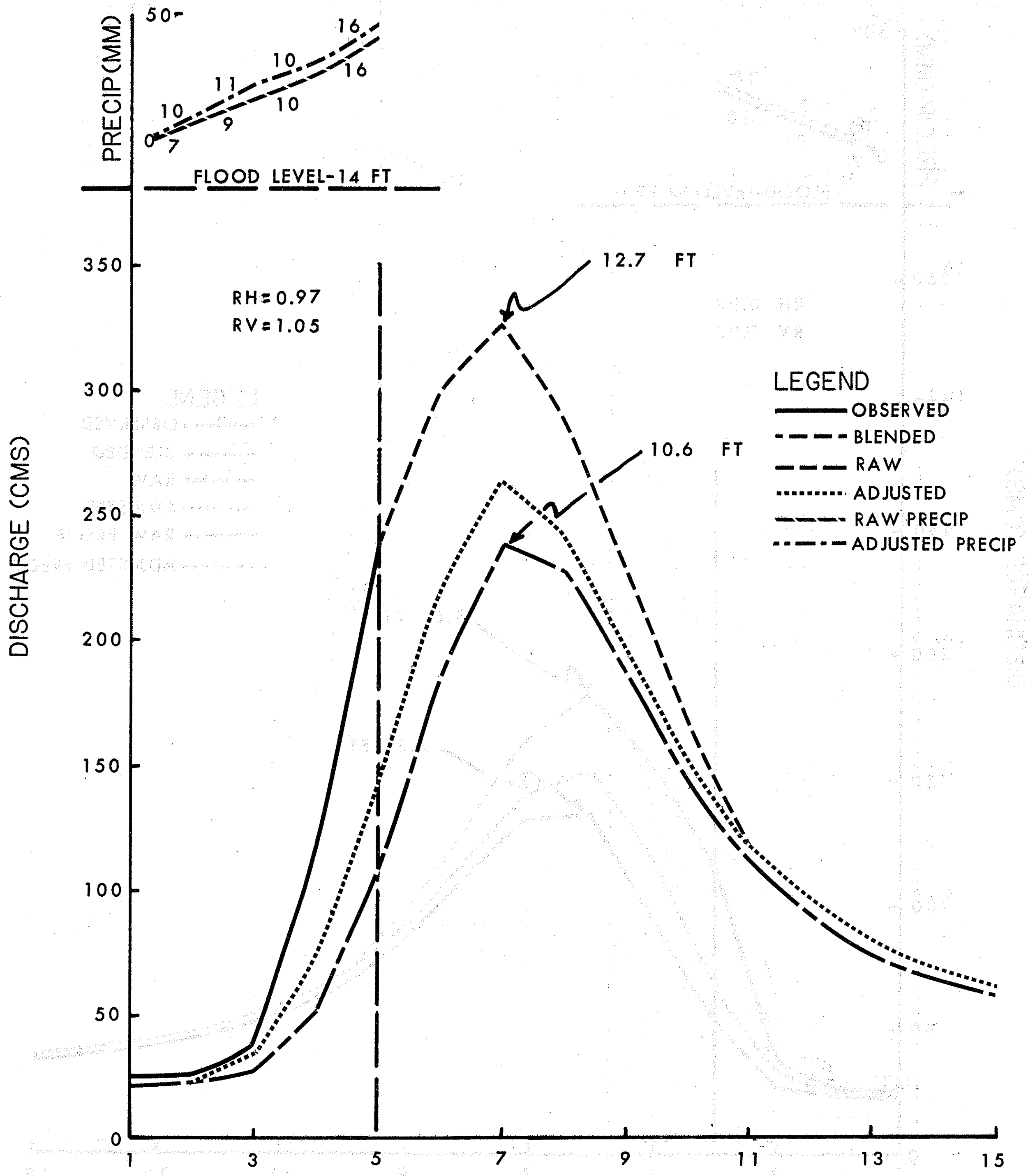


Figure 6.36--Example 5, NFORC=5

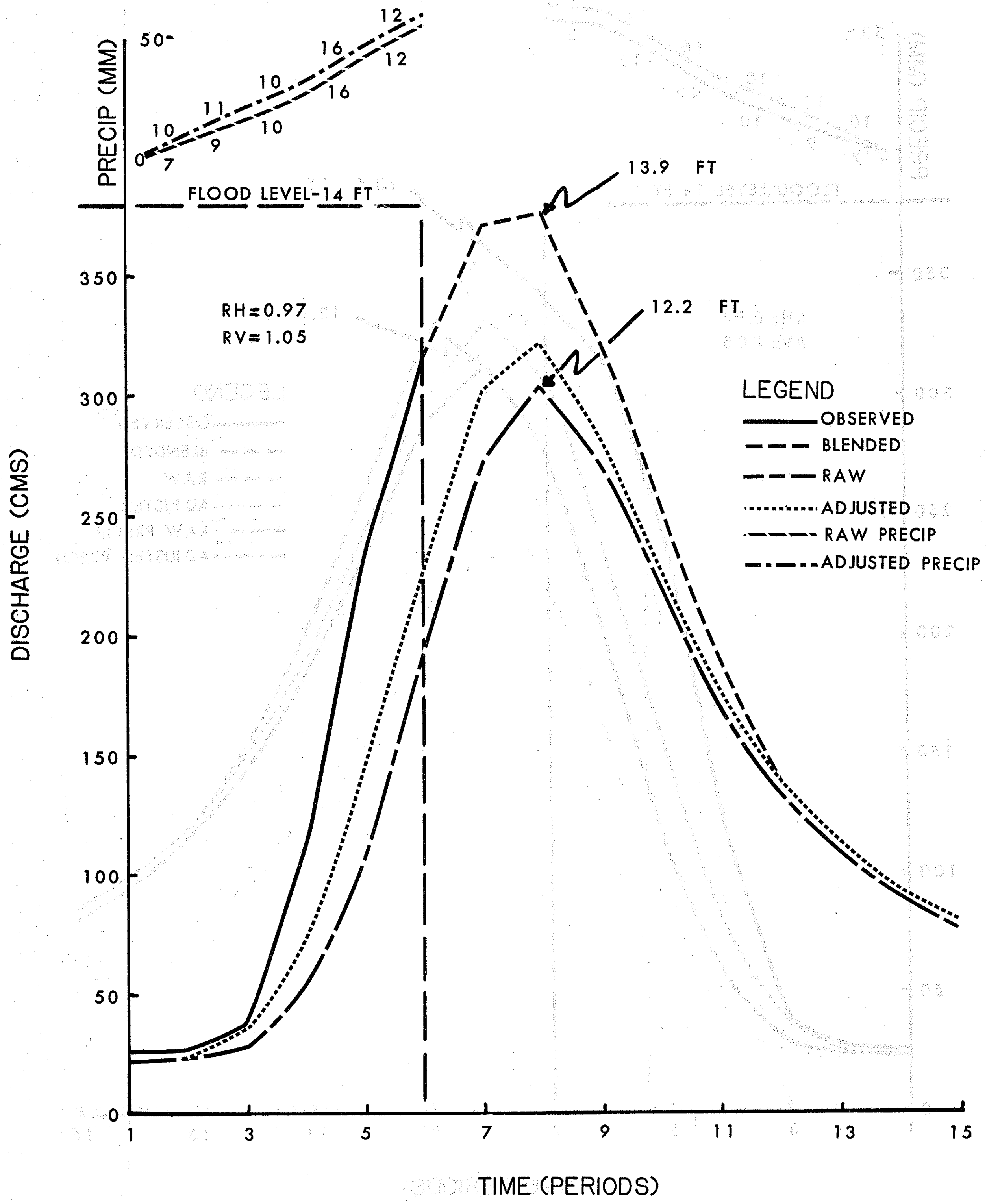


Figure 6.37--Example 5, NFORC=6

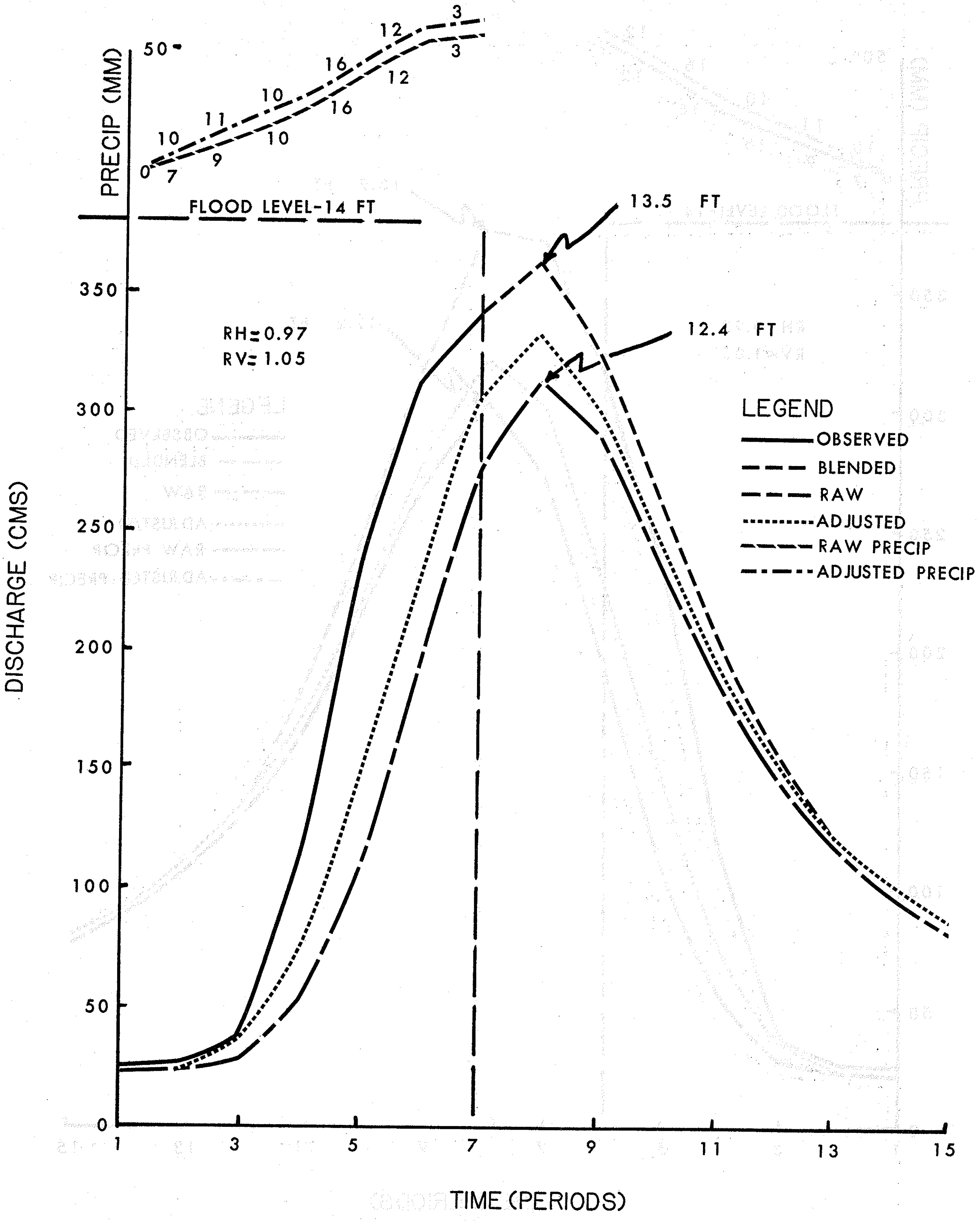


Figure 6.38--Example 5, NFORC=7

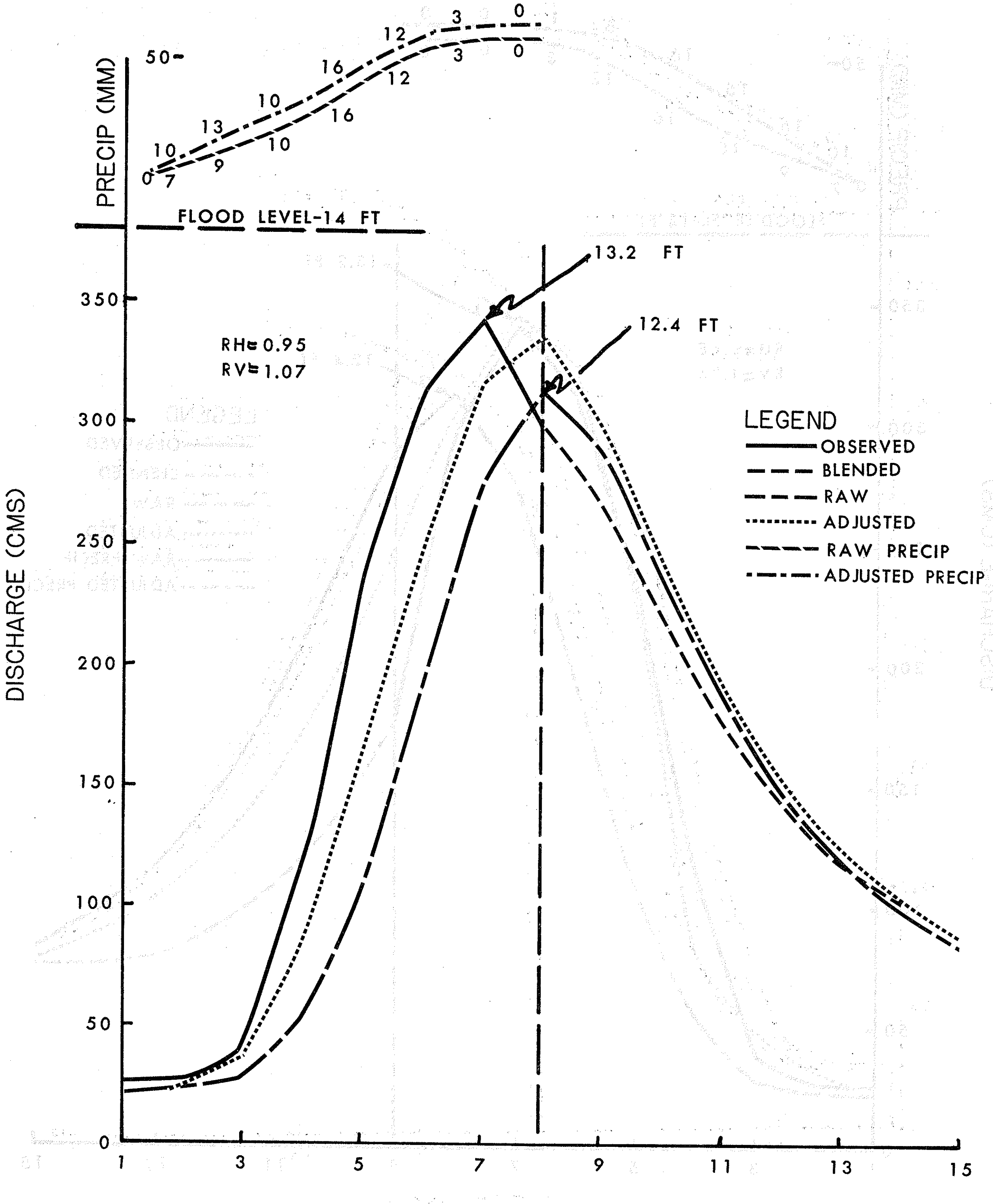


Figure 6.39--Example 5, NFORC=8

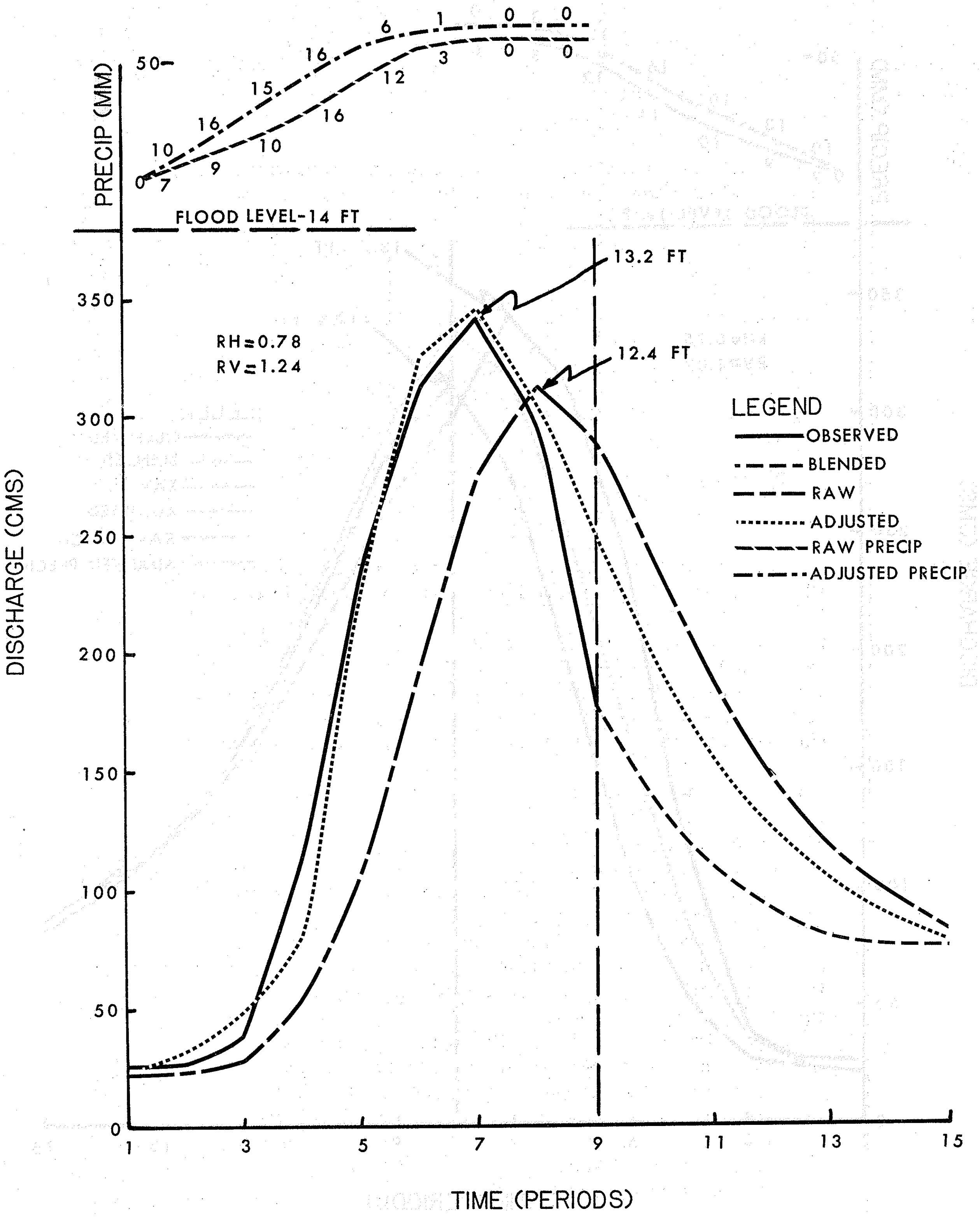


Figure 6.40--Example 5, NFORC=9

Example 6

Example 6 occurred on the Leaf River near Collins, Mississippi, on November 12, 1961. This example demonstrates the use of the CHAT procedure on an event that is a result of a nonuniform rainfall distribution over the catchment.

NFORC 7: After 130 mm of precipitation, the raw simulation is somewhat higher than the observed hydrograph, and CHAT lowers it slightly. Since it is still very early in the rise, large adjustments would not be justifiable at this time.

NFORC 9: For the last 12 hours the rain has essentially stopped, but the river has been rising very rapidly. There is a 41% disagreement between the base simulation and the latest observation, which already exceeds the forecasted peak. Yet, CHAT assesses the fit to be satisfactory and makes no adjustments. In light of the above facts, it appears that the tolerance is being too easily satisfied. Consequently, CHAT's decision to make no adjustments is not good.

NFORC 11: No significant precipitation has occurred in the past 12 hours and the observed hydrograph is beginning to level off. There is still a large discrepancy between the simulated and the observed hydrographs, and CHAT makes adjustments to the precipitation and the unit graph until the tolerance is reached. These adjustments reduce the difference somewhat, but probably not to the extent that a human forecaster would judge sufficient.

There are two questions to consider at this time: first of all, why is the CHAT procedure accepting simulations that for the most part are not suitable, and secondly, if the adjustment process were allowed to continue further, could CHAT indeed produce a hydrograph that more closely resembles the observed hydrograph of this example? In answer to the first question, the tolerance is still quite large at this time because it is a function of the stage of development of the runoff event, and NFORC 11 in this example is still quite early in the rise. However, the research for the tolerance was performed on catchments having a much shorter time to peak than the Leaf River. This example indicates that when dealing with slower responding catchments, it may be necessary to tighten the tolerance at the earlier periods in order for CHAT to adequately adjust the input at those times. This is accomplished by decreasing the exponent EX1 in the WP weight. (Note that even though the tolerance could be decreased by reducing PCOB, the change should not be made in this manner. PCOB represents the degree of confidence in the stage-discharge relationship and that has not had reason to change in this case.)

In regard to the second question, CHAT was re-run on this example without any restraint from the tolerance; the adjustments were allowed to continue as long as they could still produce improvements in the objective function. CHAT was able to produce simulations at the earlier periods that more closely matched the partial observed hydrographs, but in doing so, produced future portions of the simulations that were far too high and, consequently, had to be revised downward at later forecast times. It appears that the model may not be capable of closely duplicating the river's response in this event with a lumped input. It would therefore not be prudent to force a very close fit at these periods at the expense of the data. Indications are that an EX1 value around 0.5 would be appropriate.

NFORC 12: The rain has stopped and the observations are beginning to fall. CHAT is slowly increasing the simulation in an effort to match the observations. Although not shown on the plot, the simulation with EX1 equal to 0.5 is higher at this time as a result of the adjustment process having been carried out further at earlier periods, and is, therefore, closer to the observations.

NFORC 14-17: In response to 26 mm of additional rainfall in the past 24 hours, the observed hydrograph is beginning to rise again. Now that the river is rising once more, the CHAT simulations and the observations at these times agree very nicely. The blended hydrographs are predicting, on the average, a peak of approximately 17.5 feet at period 16.

NFORC 18: It is observed that the rise peaked at 17.6 feet at period 17. Now that the rain has ceased, the volume under the CHAT simulation is very good and far better than that of the raw simulation.

In summary, this event occurred as the result of a very nonuniform rainfall pattern over the catchment. The CHAT procedure can compensate for some degree of nonuniformity by altering the temporal distribution function (unit graph) on an event basis. However, this does not preclude the idea of using a distributed input for events such as this one. Although CHAT is not currently designed to operate on a catchment that has been sub-divided, some thought has been given to such a modification. Further ideas on this topic are discussed in Chapter 7 "Suggestions for Future Research". When using CHAT on an event such as this one, where the discrepancy might originate from the use of a lumped input rather than the data itself, it is concluded that a very close fit should not be forced by unrealistic adjustments to the input since this may cause harmful effects in the future portion of the simulation. In spite of a few difficulties with CHAT's simulations on the rising limb, the procedure still performed its function of adjusting the volumes by the end of the runoff event very nicely. Consequently, the forecaster could have a fair amount of confidence in the soil moisture variables going into the next event.

This example also provided some insight into choosing parameter values. The research value for EX1 was found to be inappropriate for slower responding catchments such as the Leaf River near Collins, and as a result, did not permit the adjustment process to be carried out far enough during the earlier periods in this rise. This problem was corrected by decreasing the value of the exponent, thereby tightening the tolerance at the earlier periods.

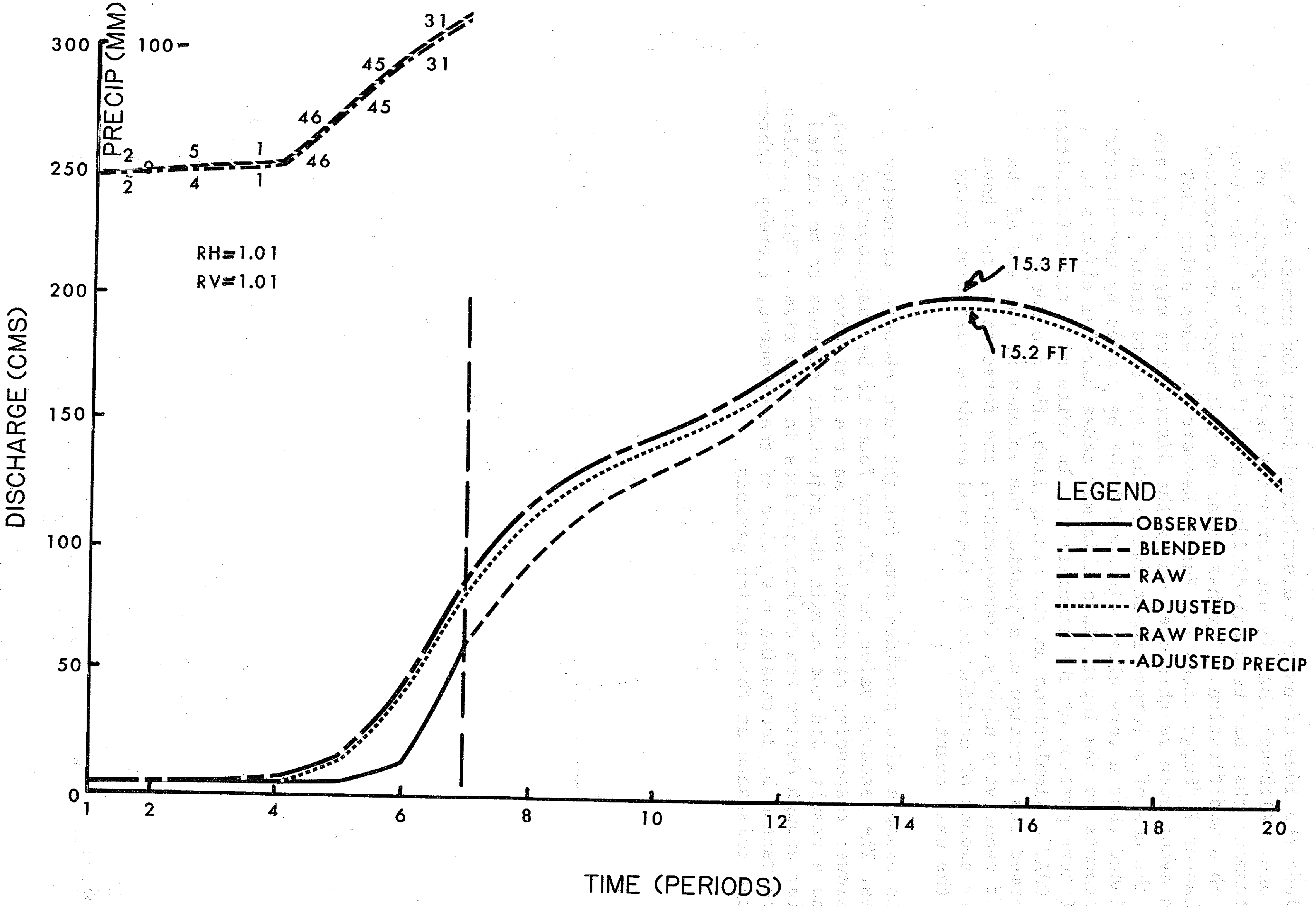


Figure 6.41--Example 6, NFORC=7

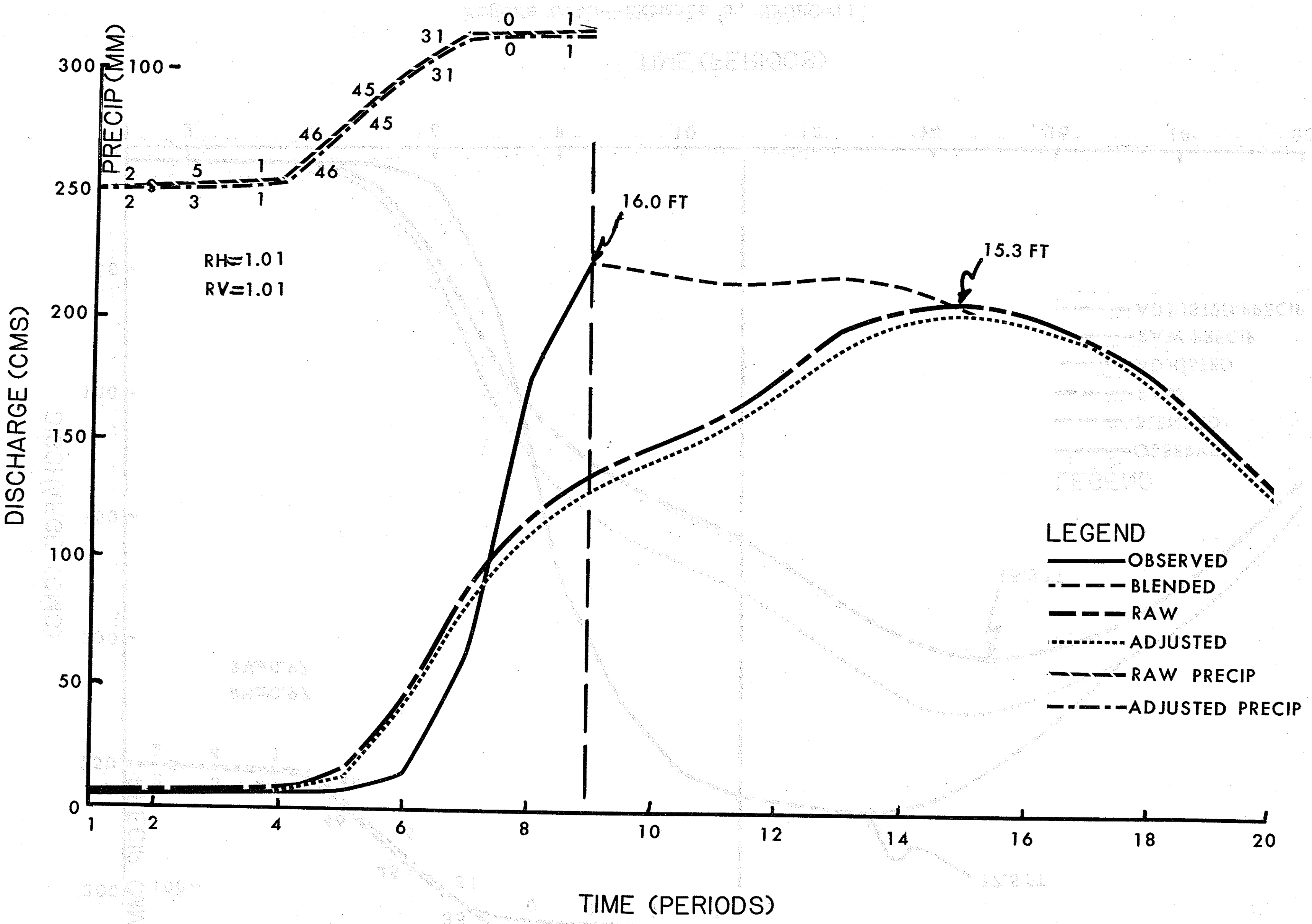


Figure 6.42--Example 6, NFORC=9

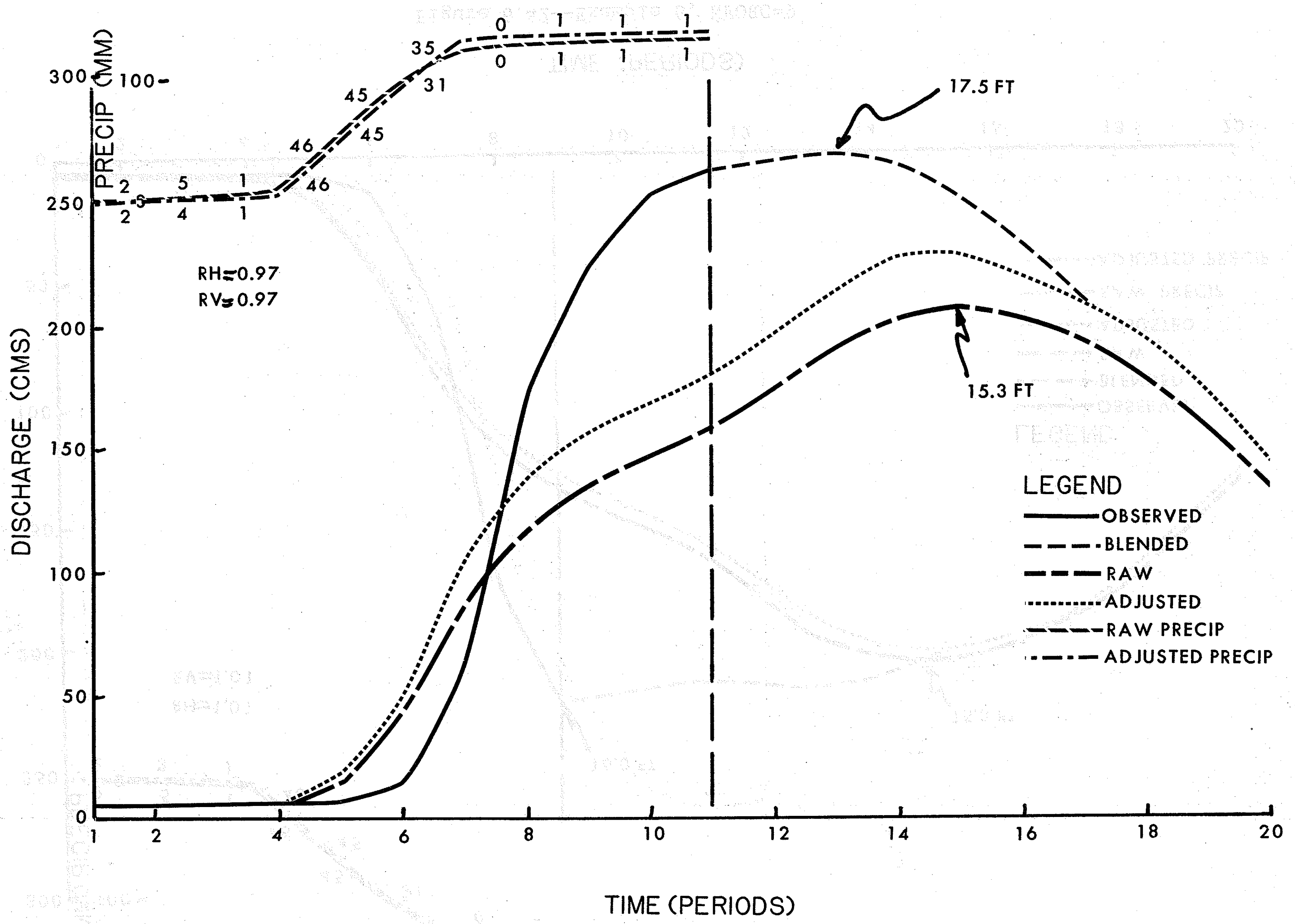


Figure 6.43--Example 6, NFORC=11

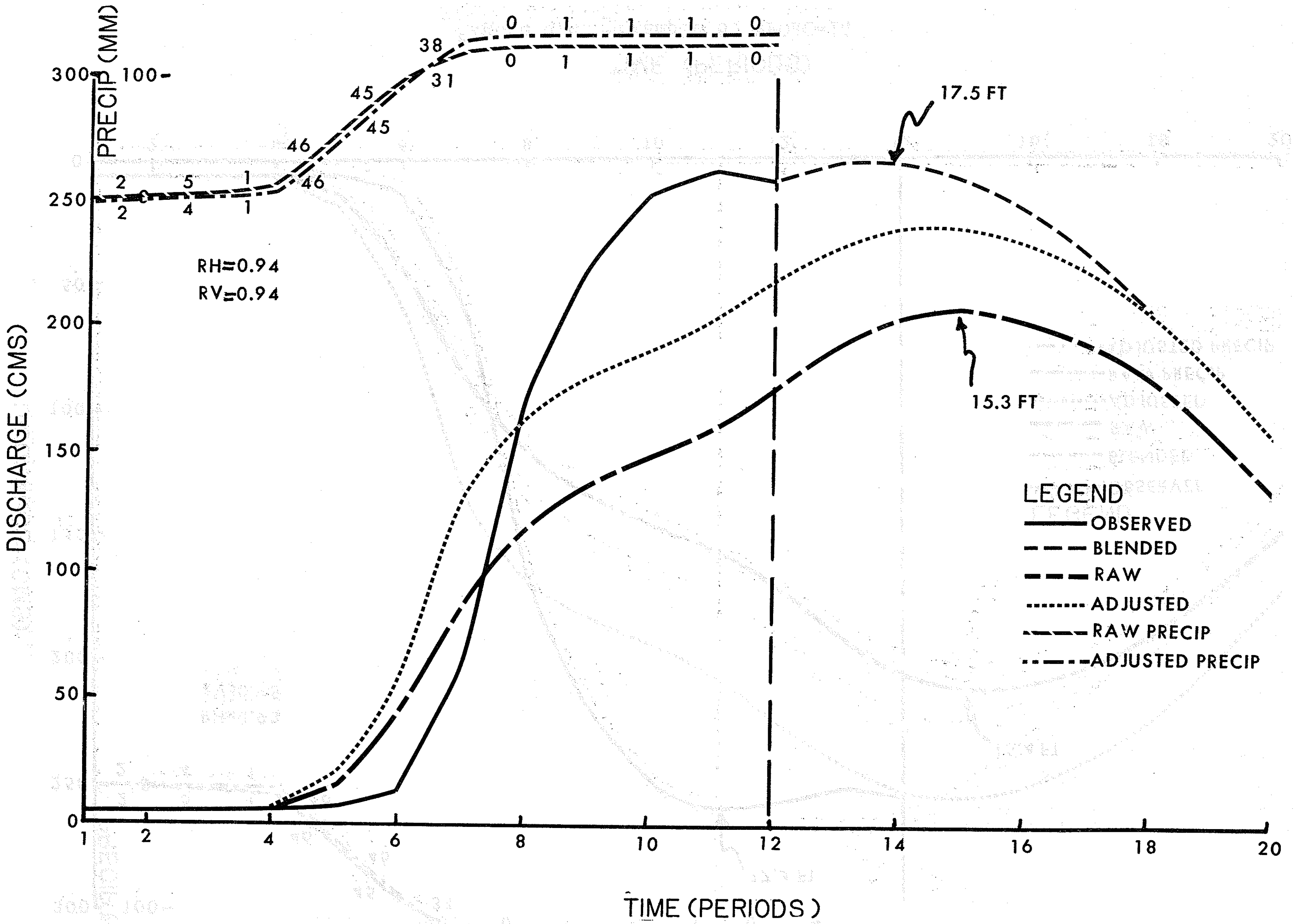


Figure 6.44--Example 6, NFORC=12

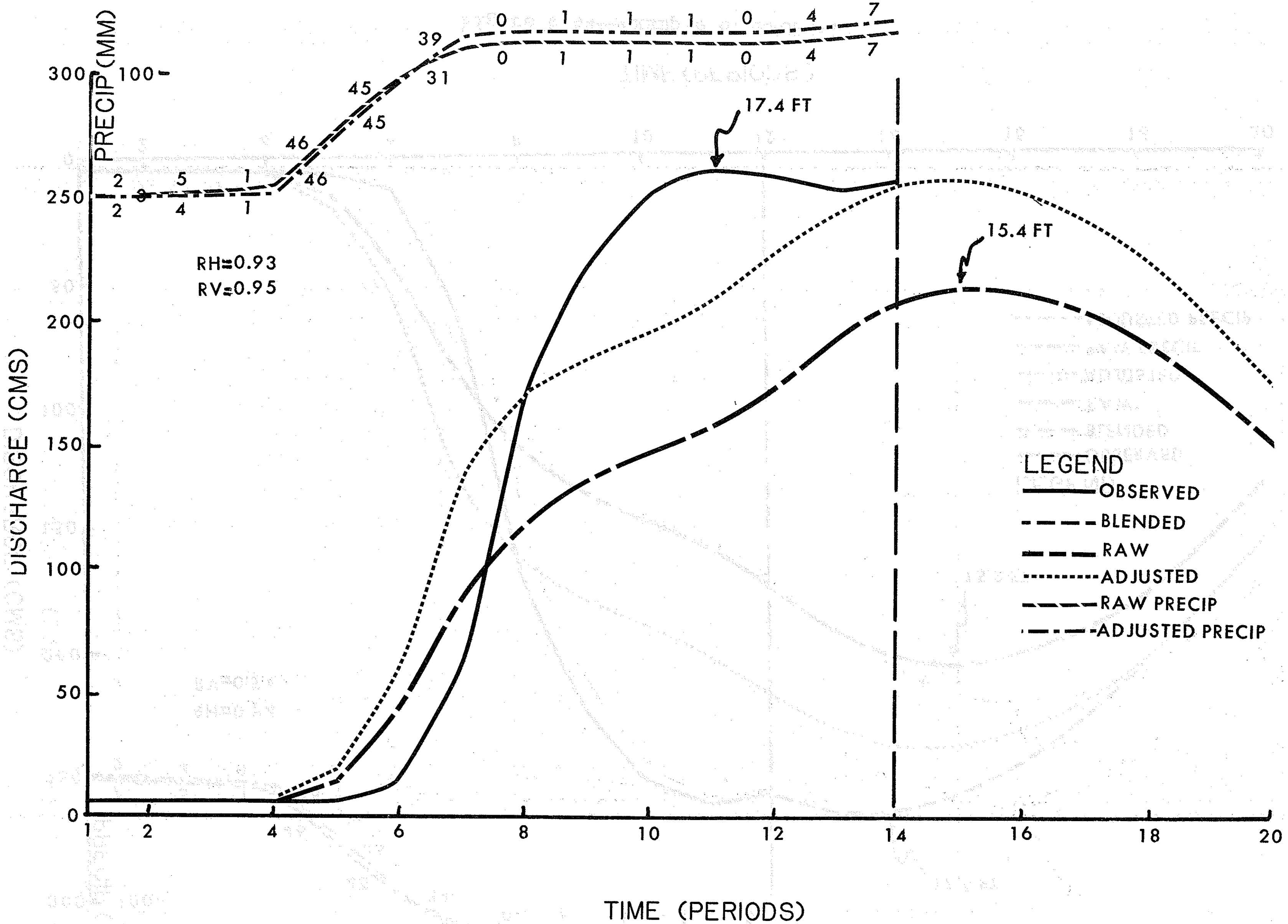


Figure 6.45--Example 6, NFORC=14

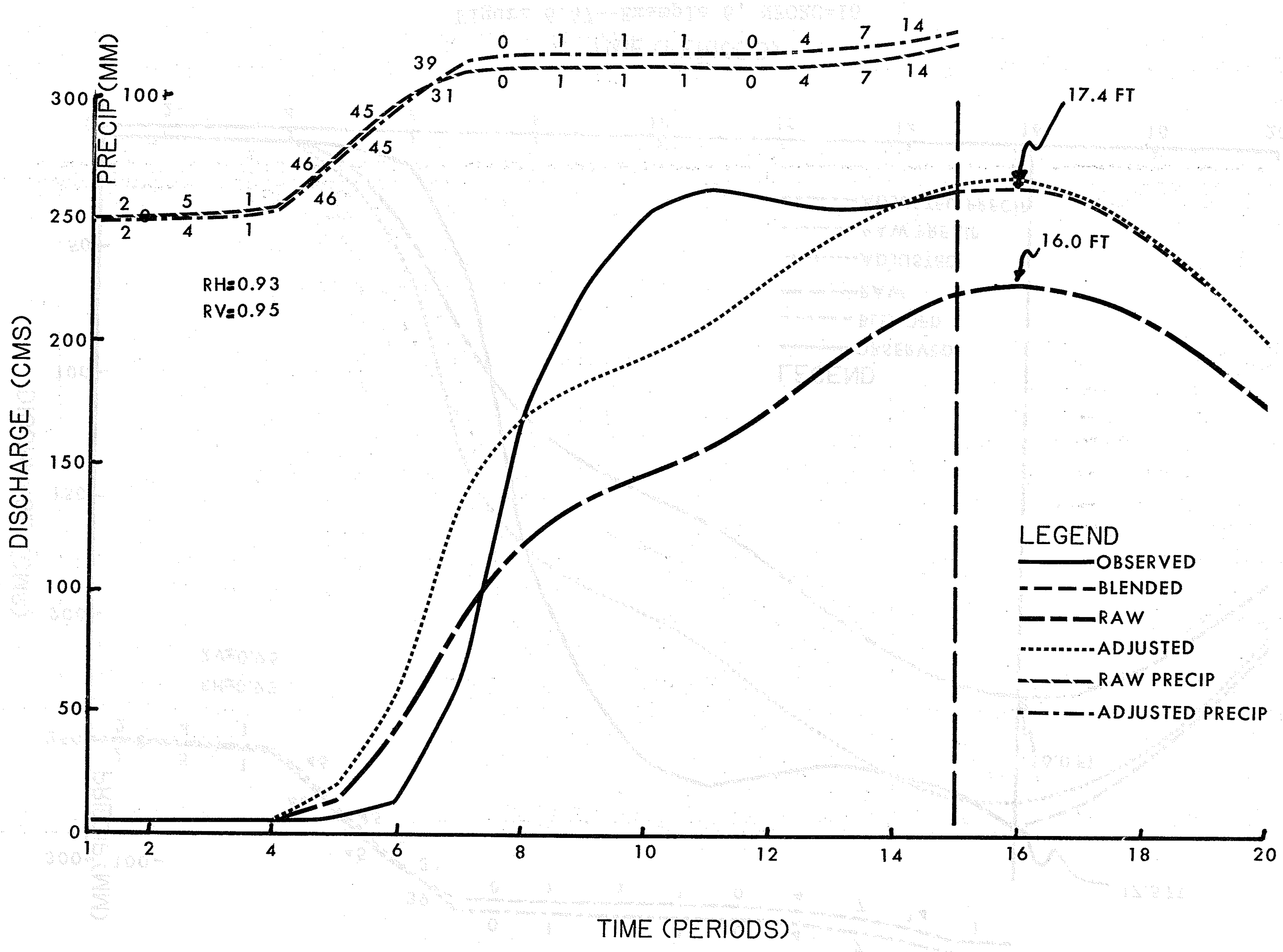


Figure 6.46--Example 6, NFORC=15

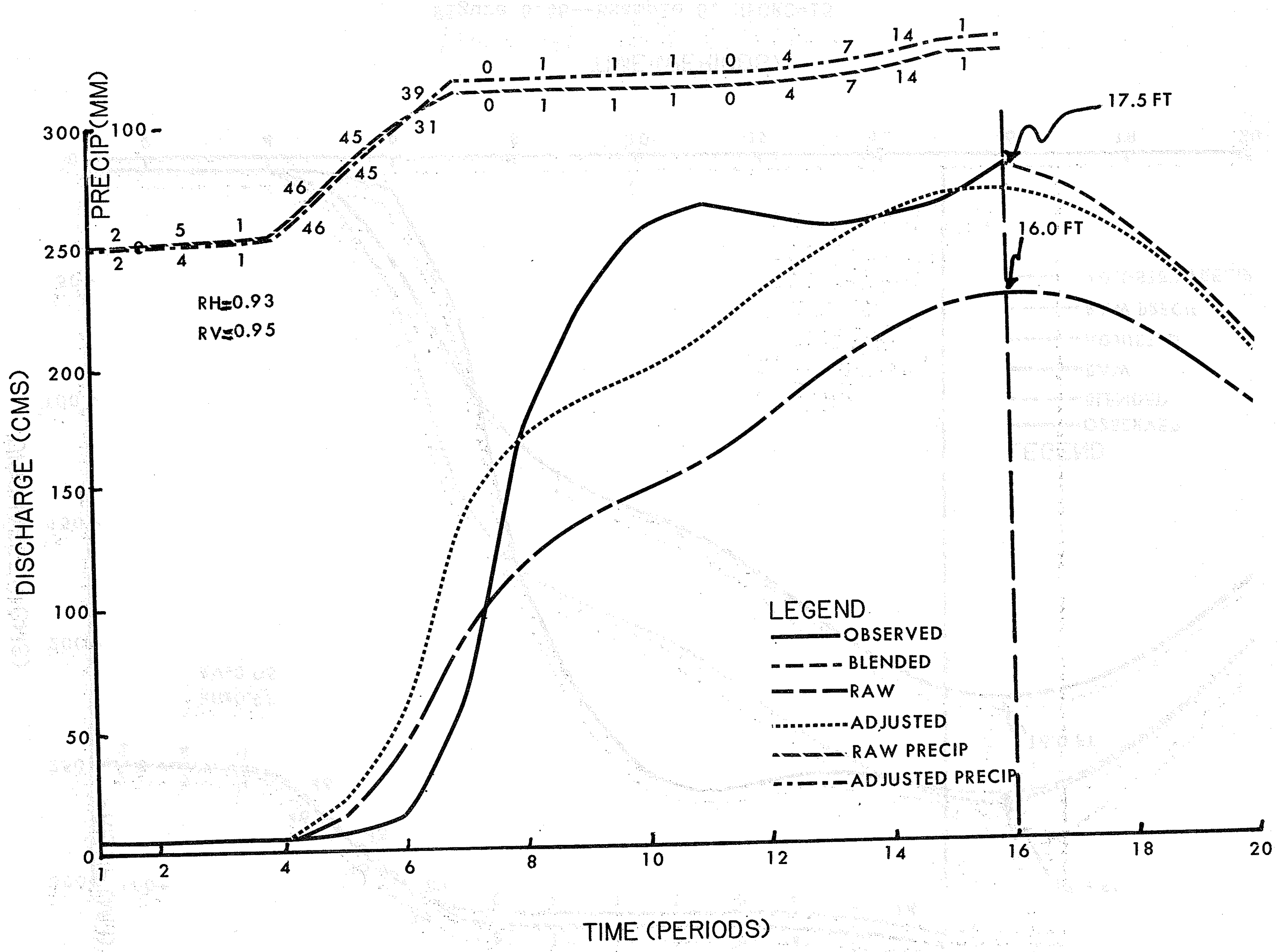


Figure 6.47--Example 6, NFORC=16

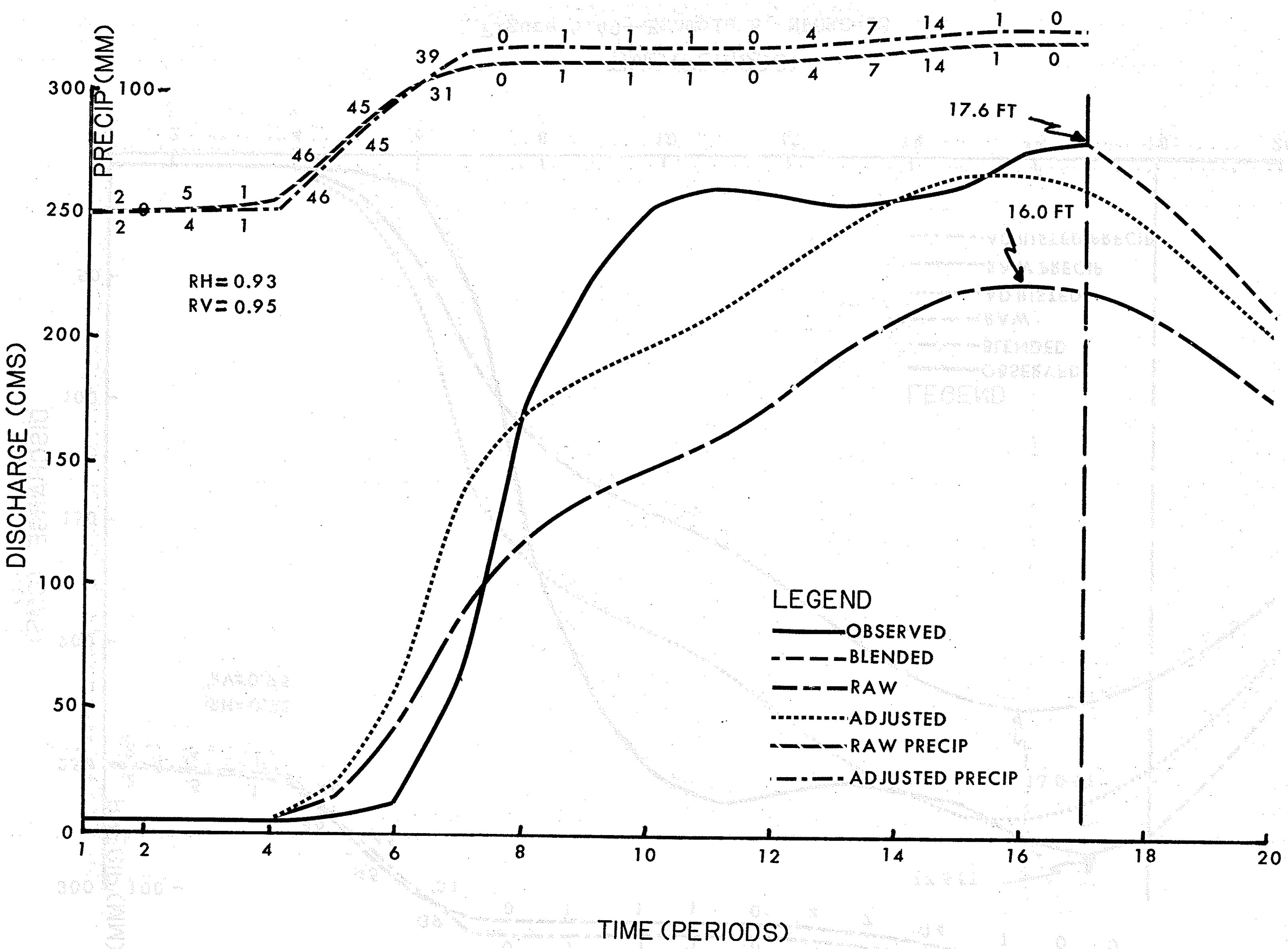


Figure 6.48--Example 6, NFORC=17

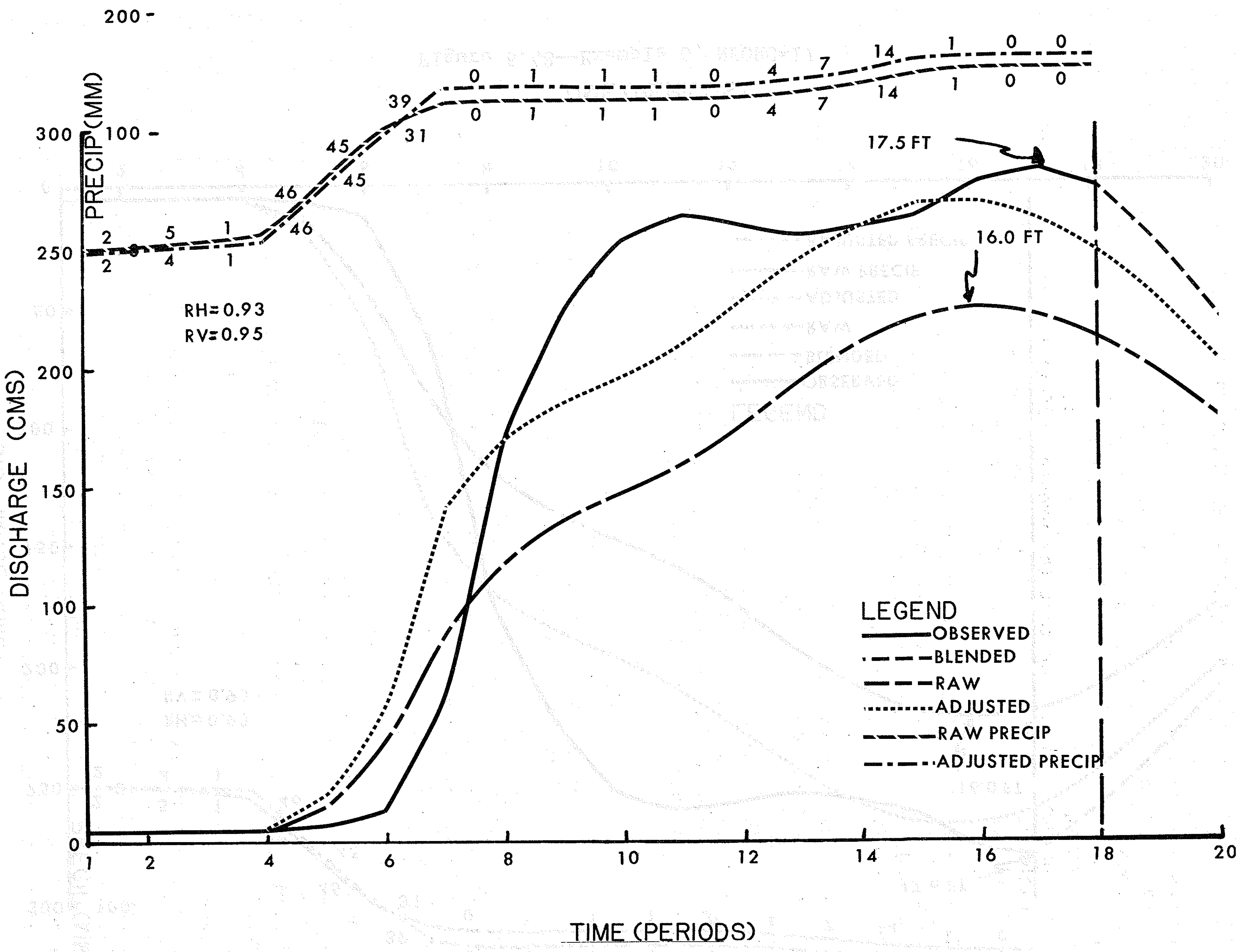


Figure 6.49--Example 6, NFORC=18

7. SUGGESTIONS FOR FUTURE RESEARCH

As was pointed out in Chapter 2, the complete solution to the problem of adjusting simulated hydrographs to agree with river observations must involve a number of techniques, each associated with a different flow regime or a different type of flow point. These techniques were associated with four phases of research and it was further pointed out that the present effort has been concerned only with phase 1, the outflow from an individual catchment during runoff events resulting from liquid precipitation.

It was also explained in an earlier section that the phase 1 solution may be subject to some modification in light of experience with the method, and that certain types of additional research on the phase 1 problem may be worthwhile.

The purpose of this chapter is to present the thoughts and recommendations of the authors in regard to the phase 2, 3, and 4 problems, and to possible future research on, and modification of, the phase 1 solution. This chapter contains no answers or solutions; those can result only from further research. It contains the authors' recommendations on how that research should be approached, based on their understanding of the problems and their experience with phase 1.

Phase 2

Outflow from Individual Catchments During Runoff Events in which Snow or Snowmelt is Involved

Runoff events of this type may involve three types of input, liquid precipitation (rain), solid precipitation (snow), or the melting of an existing snow cover. Representing these by the symbols R, S and M, there are seven possible types of occurrences, R, S, M, R-M, R-S-M, S-M and R-S. It should be noted that when R and S are both involved, this may be because the precipitation changes character during the event, or because snow is falling at the higher elevations and rain at lower levels. Of the seven combinations noted above, two need not be considered here. The "R" event is phase 1 and the "S" event produces no runoff. The remaining five will be discussed individually.

M event:

This situation involves the melting of an existing snow cover as the result of heat transfer from the atmosphere or from the soil, but not from rainfall. If the discrepancy between the simulated and the observed hydrograph is assumed to result from errors in the input to the catchment model, that input is the computed snowmelt. The solution then would be similar to the phase 1 solution, but the adjusted values of snowmelt would have to be carried back into the snow ablation model and suitable adjustments made to the remaining snow cover. It is likely that changes should be made in the constraints and in the size of the tolerance.

R-M event:

In this situation, the rain may be falling only on the snow cover and slightly accelerating the melt process, or it may be falling on bare ground in portions of the catchment. This type of event typically produces somewhat greater runoff volumes than the pure melt situation described above. Most of the additional runoff results from the rain itself; additional snowmelt caused by heat transfer from the rain is slight. This also appears to be a case in which the phase 1 technique is basically applicable but the adjustments to the input data must be distributed between the rain and the melt. The development of a rationale for doing this will probably involve additional research. In addition, such situations typically result in areal distributions of runoff which differ greatly from those exhibited by pure rain events. Thus, it may be necessary to widen the constraints on the unit hydrograph warp coefficients.

R-S-M event:

This is a situation in which snow falls during a portion of the event and then turns to rain; or, parts of the catchment may receive only rain. There may or may not be a pre-existing snow cover. If there is no pre-existing cover, the situation is very similar to the phase 1 problem and the phase 1 solution should be able to handle it. Sizeable simulation errors may result from incorrect classification of precipitation as rain or snow, but the ability of CHAT to shift precipitation input from one period to another should make it capable of dealing with this. If there is a pre-existing cover, the situation is then practically the same as the R-M case discussed above.

S-M event:

This situation usually involves a snowfall followed by a warming trend. It can be thought of and treated as two events, both of which have been discussed.

R-S event:

Since melt is not involved in this type of event, it is pretty well limited to the case in which a storm consists of rain at low elevations and snow at higher levels, and the portion of the catchment receiving rain is free of snow cover prior to the event. This then is the same problem as is encountered in phase 1 when a rainfall event is highly nonuniform. The only modifications necessary would be either wider constraints on the warp coefficients or a subdivided catchment approach. The latter has been alluded to in Chapter 6 and will be explored further in this chapter.

The above discussions are not intended to imply that the phase 2 technique should consist of five separate procedures corresponding to the five types of events discussed. The recommendation is that the research on this phase should investigate the five types individually and when an understanding of what is required for each has been acquired, then it should be possible to combine these into one procedure capable of handling any event involving snow or snowmelt. It appears likely that this procedure would be similar to the phase 1 solution, but would involve an interaction with the snow accumulation and ablation model. The need for a distributed catchment approach is a strong possibility.

Phase 3
Outflow from Individual Catchments During Low Water Periods

Discussion of the phase 3 problem should probably begin by defining what is meant by a "low water period." The most direct definition is that it is any time that a flow regime of the type handled by the phase 1 solution is not occurring. During the discussion of the phase 1 problem in previous chapters, the term "runoff event" was never objectively defined; it was assumed that a forecaster would know when he was involved in such an event and would then operate his forecast program in the "CHAT mode" until the end of the event. This is a valid assumption. At some future time however, when the combination of techniques, phases 1 and 3, are operating so as to continuously keep a model in line, it will probably be necessary to have an objective and hydrologically based criterion to indicate when to switch back and forth between the two methods. Such a criterion would have to be of the "either or" type. That is, if the model is doing certain things, or if the river is doing certain things, then a runoff event is occurring. Perhaps the model indication would be the exceedance of a particular threshold value of runoff from the upper three components. A suitable threshold value would have to be determined by study and it may vary regionally. The river indication might be an increased flow such that the net discharge above an estimated base flow corresponds to that threshold value of upper level runoff. The occurrence of either of these indications would put the procedure in the phase 1 mode, and it would remain in that mode up to a point in time equal to the end of upper level runoff plus the length of the unit hydrograph base. At all other times, it would be in the phase 3, or low water, mode.

With such a definition, the model input during a low water period would consist of precipitation and potential evapotranspiration just as it does in phase 1. In this case, however, it appears that the principal source of simulation error would be the PE. Errors in the determination of mean areal rainfall during such a period would probably not affect the long-term tracking of the model appreciably. Or, if they did, perhaps the slack could be taken up by the adjusting of the evapotranspiration computations.

In some applications, the model uses a normal PE curve rather than actual values and, even when actual values are used, a time-invariant adjustment curve is involved. Both normal PE and the adjustment curve are subject to sizeable errors, especially during long-term departures from climatic normals. It therefore appears that the adjustment of model output during low water periods might best be accomplished by adjusting the observed/computed/normal PE and/or the adjustment curve. Or, perhaps just the figure representing catchment demand could be adjusted.

If this approach is used, a question which arises is how far back in time to go. Since the pertinent mechanisms in the model are slow acting, it may be necessary to iteratively change the input over an extended period, perhaps thirty days or longer. On the other hand, since the adjustment procedure will be applied every day, what is done on any single day may involve only a short period of input, the earlier periods having been adjusted previously. This concept is similar to that behind the phase 1 strategy which operates every six hours and concentrates on the few precipitation periods which have a substantial effect on the objective function at that particular time. In any event, adjustment of input could not go further back in time than the end of the last runoff event.

Whatever period is involved, the decision variables, in the case of PE, might be the only actual daily values. This could present problems since the serial correlation of such values is high enough that they should not be considered independent variables. Also, if the period being adjusted is long, their great number could make the process unwieldy. Perhaps some sort of warping operation performed on the whole series would be preferable.

If the adjustment curve is to be changed, no obvious problem exists as this is normally defined by just a few points.

The objective function in the phase 3 problem should be based on daily volumes, perhaps:

$$\Sigma|(\overline{QO}-\overline{QS})|$$

where QO and QS are the observed and simulated mean daily discharges and the summation is made over a period of perhaps the last five days.

In determining the observed mean dailies, some problems may arise due to diversion and regulation. Diversions not noticeable during runoff events may involve substantial portions of the flow during low water periods. Artificial regulation during such periods may cause the instantaneous flow at the time of an observation to differ from the mean daily by an order of magnitude. And, since such regulation often exhibits a diurnal pattern, the differences are not always random. These problems, where they exist, must be solved. To detect, analyze, and treat these matters will involve investigating aspects of the flow regime in which Weather Service offices have not traditionally been interested. Nevertheless, if these factors are ignored or if they are treated by expanding the tolerance to such magnitudes, any effort to keep the model's moisture accounting in line will be rendered totally meaningless.

In the case of forecast points subject to excessive regulation, a solution to the problem may lie in the use of the U. S. Geological Survey's "Data Relay" system if the gage is part of that system. The stages at such stations are relayed in real time, via satellite, to the U.S.G.S. computer in Reston, Va. There they are available, within a few hours, for interrogation by any high-speed terminal. The frequency of observation is the same as the frequency of on-site tape punching.

At the present time, less than 300 stations have this capability, but the system is expanding and one of the criteria is user need. Further details may be found in U.S.G.S. Circular 756, "Collection, Storage, Retrieval and Publication of Water Resources Data."

The tolerance should reflect primarily the accuracy of the low water rating and the effect of both the accuracy and the precision involved in observing and telemetering stages. The tolerance may have to be somewhat larger just after runoff events and some sort of transition from a type 1 tolerance to a type 3 may be needed.

Finally, if the adjustment is to be accomplished solely by manipulating PE input, one cannot exclude from consideration the unhappy situation in which such input has been reduced to zero and the model still generates too little water. If this happens, and if it is real rather than observational, there are three possible causes. They are, in order of likelihood:

1. Errors in model parameters, particularly maximum storages and depletion coefficients.
2. A need to adjust precipitation values during the low water period.
3. Erroneous storages at the end of the last runoff event; a deficiency of the phase 1 operation.

Phase 4

An Adjustment Technique Applicable to Points in a River System that are not at the Outlets of Individual Catchments

The hydrograph at a downstream point is modelled by the execution of one or more catchment analyses and one or more channel routing operations. The errors in such a simulation reflect the combined effect of errors in both types of computation. The accuracy of a channel routing operation is very much higher than that of a catchment model. Further, it is probably safe to assume, tentatively, that if errors in the catchment analyses could be eliminated, the residual discrepancy in the simulation, reflecting only routing errors, would be small enough that it could be reconciled by a blending procedure. It is therefore recommended that initially no thought be given to making CHAT type adjustments to the routing operation. One possible exception to the foregoing is the case of channels which involve substantial bank losses at high flows. Whatever type of model is used to analyze this phenomenon may indeed generate large errors and may require some type of real time adjustment. It should also be noted here that, with the possible exception of the bank loss problem, channel routing models do not involve soil moisture accounting and the problem of correcting soil moisture variables along with the model output does not exist.

If then the adjustment of hydrographs at downstream points is to be accomplished by making phase 1 type adjustments to the contributing catchments, phase 4 should consist only of a variation of the phase 1 solution. If it can be further assumed that all upstream forecast points have been observed and adjusted, and this is admittedly a tenuous assumption, then the only catchment which should be adjusted is the "local" area immediately above the forecast point. What is involved then is basically a phase 1 type operation in that area. If, due to a poorly operating operational network, one or more headwater points have <u>not</u> been observed and adjusted, they will have to be treated along with the local area. Because of the time lag in the channel system, and because of the nature of the phase 1 strategy, such a procedure should be workable even though the number of decision variables appears to be large.

For this type of solution it will probably be necessary to make some changes in the method of computing both the objective function and the tolerance. The development of these was based on concepts appropriate to catchment simulation. The simulation of a downstream point may well require the changing of some of those concepts. For instance, the method of computing the timing weight in phase 1 is based on the assumption that timing errors of less than three hours should be ignored. In phase 4, where it is desired to ignore routing errors completely, some other interval based on the accuracy of the routing procedure may be more appropriate. Further, it may be necessary to recognize that the early part of the hydrograph, which consists primarily of local catchment outflow, may have to be treated differently than the later part which consists mainly of routed upstream flow.

This completes the discussion of the phase 2, 3, and 4 problems. The remainder of this chapter is devoted to possible further work with phase 1, specifically further testing of the adjusted soil moisture variables and application to a distributed input catchment model.

Further Testing of Adjusted Soil Moisture Variables

In Chapter 1 it was explained that CHAT is intended to serve two purposes; adjustment of the model output, and adjustment of the soil moisture variables, so as to produce a more accurate simulation of the next runoff event. This latter purpose is also implied by the title of this report. In the research so far, all of the verification of CHAT was based on an analysis of the adjusted model output, and no attempt was made to determine if the adjustments actually would improve the model's performance for a period into the future. Such an investigation would be a worthwhile research effort.

To accomplish this would require the simulation of a long period of streamflow in two different modes. The first mode would be a normal simulation in which no adjustment to the model's output is made. In the second mode, each runoff event would be adjusted using the CHAT phase 1 technique. The model would then advance to and through the next event, making a raw simulation. After determining the error statistics for that simulation, it would back up, re-run the event making CHAT adjustments, proceed to the next event, and so on. The comparison of error statistics would be between the simulations made in the first, free-wheeling mode and those resulting from the raw simulations in the second mode when the soil moisture variables in the preceding runoff event have been adjusted by CHAT. The statistics should be based on the error in the total runoff volume and the analysis should relate the errors to the time which has elapsed since the last event.

Of the events studied in the research, there was only one which might have shed some light on this aspect of CHAT's performance and that was the closely spaced Connie-Diane storms in the Monocacy basin. Unfortunately, the raw simulation of the Connie event was quite good and the slight changes made by CHAT during that event did not produce large changes in the values of the soil moisture variables at the end. Consequently, the raw simulation of the Diane storm was about the same whether or not Connie had been adjusted.

Application to a Distributed Input Catchment Model

All of the research on CHAT phase 1 has been based on the use of a lumped catchment model. Investigations into the use of distributed input - distributed parameter applications of conceptual catchment models have taken place concurrently with that research (Morris, 1975, 1977). It appears at this writing that the use of distributed models in certain types of catchments may not be far off, and it is therefore appropriate to consider how the CHAT technique might be applied to them.

Basically, such an application would consist of having a separate set of six hourly mean areal precipitation values for each zone within the catchment, and perhaps a set of warp coefficients for each zone. The only obvious problem is that this may increase the number of decision variables to an unmanageable quantity. For instance, with three zones and a two-day storm, there would be 30 variables to be manipulated. This would probably not be a problem, however, since at any particular forecast time, only two or three of the precipitation periods in each zone would be in a "working position." Further, the use of the distributed input model may well eliminate the need to manipulate the unit hydrograph. This would mean that the warp coefficients and the warp subroutine could be removed from the operation.

A question which arises is just how the CHAT strategy would operate in such an application. That is, would the change in precipitation be limited to one per pass, or would it be one per zone per pass? Would the changes be controlled by one beginning sensitivity figure for the catchment, or would there be a separate sensitivity figure for each zone?

The answers to these questions can be determined only through research. At this time, however, there seems to be no reason to think that CHAT cannot be used successfully with a distributed model if applied along the lines described above.

REFERENCES

1. Tribus, Myron, 1969: Rational Descriptions, Decisions and Design, Pergamon Press, Inc., Elmsford, N. Y., 478 pp.

2. Morris, David, 1975: "The Use of a Multizone Hydrologic Model with Distributed Rainfall and Distributed Parameters in the National Weather Service River Forecast System", NOAA Technical Memorandum NWS Hydro-25, U.S. Dept. of Commerce, Silver Spring, Md., 15 pp.

3. Morris, David, 1977: "Streamflow Synthesis in Employing a Multi-zone Hydrologic Model with Distributed Rainfall and Distributed Parameters", Ph.D. Dissertation, Oklahoma State University, Stillwater, Okla.

APPENDIX A

SUBROUTINE LISTINGS

Subroutines are available to IBM 360/195 users in the following library:

NWS.RFS.ARCHIVE.SOURCE(CHATTERP)

NWS.RFS.ARCHIVE.SOURCE(CHATTOLR)

NWS.RFS.ARCHIVE.SOURCE(CHATOBJC)

NWS.RFS.ARCHIVE.SOURCE(CHATSTRT)

NWS.RFS.ARCHIVE.SOURCE(CHATWARP)

NWS.RFS.ARCHIVE.SOURCE(CHATBLND)

```
      SUBROUTINE INTERP(NB,TB,QB)
C**********************************************************************
C**********************************************************************
C
C              THIS SUBROUTINE INTERPOLATES BETWEEN DISCHARGE (OR STAGE)
C              OBSERVATIONS MADE AT RANDOM TIMES AND DETERMINES THE VALUE
C              AT EACH SIX HOUR ORDINATE CORRESPONDING TO THE ORDINATES
C              OF THE SIMULATED HYDROGRAPH.
C
C     SUBROUTINE INPUT -
C
C              NB     - THE NUMBR OF OBSERVATIONS (MAXIMUM 100)
C
C              TB(1) TO TB(NB) - THE TIME, IN HOURS, OF EACH OBSERVATION.
C                     ZERO OF THE TIME SCALE MUST CORRESPOND TO THE
C                     FIRST ORDINATE OF THE SIMULATED HYDROGRAPH. TB(1)
C                     MUST BE ZERO AND WILL BE SET TO ZERO IF IT IS NOT.
C                     TB(NB) MAY NOT EXCEED 234 HOURS. OBSERVATIONS MUST
C                     APPEAR IN CHRONOLOGICAL ORDER.
C
C              QB(1) TO QB(NB) - THE OBSERVED DISCHARGE (OR STAGE) AT
C                     EACH OF THE TIMES SHOWN IN THE PREVIOUS ARRAY.
C
C     SUBROUTINE OUTPUT -
C
C              NOB       -
C              TILT      -
C              QOLT      -        SUBROUTINE COMPUTES THESE QUANTITIES AS
C              PJ        -        DEFINED IN SUBROUTINE OBJEC
C              QOMX      -
C              ZZ        -
C
C              QO(N)     - THE INTERPOLATED OBSERVED DISCHARGES
C                          AT ORDINATES 1 TO NOB.
C
C**********************************************************************
C**********************************************************************
      DIMENSION TB(100),QB(100),S(100)
      COMMON/ALL/NOB,TILT,QOLT,PJ,QO(53),QOMX,ZZ
C
C              IF OBSERVATIONS ARE AT SIX-HOUR ORDINATES AND
C              ONLY THERE, SKIP THE INTERPOLATING STATEMENTS
C
      TB(1)=0.
      TILT=0.
      QOLT=QB(NB)
      NOB=TB(NB)/6.+1.01
      IF(NOB.NE.NB) GO TO 9
      DO 7 K=1,NB
      TO=ABS(TB(K)+6.-6.*K)
      IF(TO.GT..001) GO TO 9
 7    QO(K)=QB(K)
      GO TO 14
 9    TILT=TB(NB)+6.-6.*NOB
      QOLT=QB(NB)
      S(1)=(QB(2)-QB(1))/TB(2)
      K=NB-1
      DO 10 J=2,K
```

```
      WA=1./(TB(J+1)-TB(J))
      WB=1./(TB(J)-TB(J-1))
 10   S(J)=((QB(J+1)-QB(J))*WA*WA+(QB(J)-QB(J-1))*WB*WB)/(WA+WB)
      S(NB)=(QB(NB)-QB(K))/(TB(NB)-TB(K))
      QO(1)=QB(1)
      J=2
      NC=0
      DO 14 K=2,NOB
      TO=6*K-6.001
 11   IF((TO.GE.TB(J-1)).AND.(TO.LE.TB(J))) GO TO 12
      J=J+1
      NC=0
      GO TO 11
 12   IF(NC.EQ.1) GO TO 13
      Z=TB(J)-TB(J-1)
      CA=(2.*(QB(J-1)-QB(J))+Z*(S(J-1)+S(J)))/(Z*Z*Z)
      CB=(S(J)-S(J-1)-3.*CA*Z*Z)/(2.*Z)
      NC=1
 13   Z=TO-TB(J-1)+.001
      QO(K)=CA*Z*Z*Z+CB*Z*Z+S(J-1)*Z+QB(J-1)
C
 14   CONTINUE
      PJ=TILT/6.
      QOMX=0.
      DO 15 L=1,NOB
      IF(QO(L).LE.QOMX) GO TO 15
      QOMX=QO(L)
      ZZ=L
 15   CONTINUE
      IF(QOLT.LE.QOMX) GO TO 16
      QOMX=QOLT
      ZZ=PJ+NOB
 16   CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TOLER(NFORC,QS,PR,TOL)
C***********************************************************************
C***********************************************************************
C
C                 THIS SUBROUTINE COMPUTES THE TOLERANCE-THE MAXIMUM
C                 VALUE THE OBJECTIVE FUNCTION MAY HAVE WHILE REPRE-
C                 SENTING A SATISFACTORY FIT BETWEEN THE OBSERVED AND
C                 COMPUTED HYDROGRAPHS.
C
C      SUBROUTINE INPUT -
C
C                 NFORC      - THE CURRENT SIX-HOUR PERIOD, NUMBERED
C                              SEQUENTIALLY FROM THE BEGINNING OF THE
C                              RUNOFF EVENT
C
C                 QS(53)     - THE ARRAY OF SIMULATED 6-HOUR DISCHARGES
C
C                 EX1        - THE EXPONENT USED IN COMPUTING WEIGHT WP
C
C                 PCENT      - PERCENTAGE USED IN COMPUTING TOL(SEE SECT.4.2)
C
C                 NOB,QOLT,PJ,QO(N)    -   AS COMPUTED IN INTERP AND
C                                          DEFINED IN OBJEC
C
C      SUBROUTINE OUTPUT -
C
C                 TOL        - TOLERANCE FOR FORECAST TIME NFORC
C
C                 MPT        - TIME OF THE SIMULATED PEAK
C
C***********************************************************************
C***********************************************************************
      DIMENSION QS(53),PR(53)
      COMMON/MATOL/ EX1,PCENT
      COMMON/ALL/NOB,TILT,QOLT,PJ,QO(53),QOMX,ZZ,MPT
C
C                FIND CENTER OF MASS OF PRECIP(CMP).
C                DETERMINE TIME OF MAX DISCHARGE, BUT IT
C                CANNOT OCCUR BEFORE CMP.
C
      CMP=0.
      SPR=0.
      DO 5 K=1,NFORC
      CMP=CMP+PR(K)*(K+.05)
 5    SPR=SPR+PR(K)
      IF(SPR.GT.0.) GO TO 6
      CMP=0.
      GO TO 7
 6    CMP=CMP/SPR
 7    QMX=0.
      DO 10 I=1,53
      IF(QS(I).LE.QMX) GO TO 10
      X=I
      IF(X.LT.CMP) GO TO 10
      QMX=QS(I)
      MPT=I
 10   CONTINUE
C
```

```
C
C                COMPUTE WEIGHT WP--BASED ON THE TIME DISTANCE BETWEEN
C                THE LAST OBSERVED DISCHARGE AND THE SIMULATED PEAK.
C
      WP=((PJ+NOB)/MPT)**EX1
      IF(WP.GT.1.) WP=1.
C
C                PCOB IS A PERCENTAGE(INPUT-PCENT) OF THE
C                LAST OBSERVED DISCHARGE, OR THE MEAN DISCHARGE
C                UP TO THE LATEST OBSERVED, WHICHEVER IS GREATER.
C
      PCOB=0.
      DO 20 I=1,NOB
 20   PCOB=PCOB+QO(I)
      PCOB=(PCOB+QOLT*PJ)/(PJ+NOB)
      IF(QOLT.GT.PCOB) PCOB=QOLT
      TOL=(PCOB*PCENT)/WP
      RETURN
      END
```

```
      SUBROUTINE OBJEC(NFORC,QS,OF)
C***********************************************************************
C***********************************************************************
C
C                 THIS SUBROUTINE COMPUTES THE OBJECTIVE FUNCTION
C                 WHICH REFLECTS THE GOODNESS OF FIT BETWEEN THE
C                 COMPUTED HYDROGRAPH AND THE OBSERVED DISCHARGES
C                 UP TO THE TIME OF THE LAST OBSERVED DISCHARGE.
C                 THE LAST OBSERVED DISCHARGE NEED NOT COINCIDE WITH
C                 ONE OF THE SIX-HOURLY COMPUTED ORDINATES.
C
C       SUBROUTINE INPUT -
C
C                 NFORC     - THE CURRENT SIX-HOUR PERIOD, NUMBERED
C                             SEQUENTIALLY FROM THE BEGINNING OF THE
C                             RUNOFF EVENT
C
C                 QS(53)    - THE ARRAY OF SIMULATED 6-HOUR DISCHARGES
C
C                 NOB       - NUMBER OF THE LAST ORDINATE PRIOR TO, OR AT
C                             THE TIME OF , THE LAST DISCHARGE OBSERVATION
C
C                 TILT      - THE TIME, IN HOURS, FROM ORDINATE NOB TO THE
C                             LAST DISCHARGE OBSERVATION. IF TH LAST
C                             OBSERVATION COINCIDES WITH ORDINATE NOB,
C                             THEN TILT=0.
C
C                 QOLT      - VALUE OF DISCHARGE AT THE LAST OBSERVATION.
C                             IF TILT IS ZERO, THEN QOLT=QO(NOB)
C
C                 PJ        - FRACTION OF THE SIX-HOUR PERIOD COVERED BY
C                             TILT AND IS EQUAL TO TILT/6.
C
C                 QOMX      - MAXIMUM OBSERVED DISCHARGE INCLUSIVE OF QOLT.
C
C                 ZZ        - NUMBER OF THE ORDINATE AT WHICH QOMX OCCURS.
C                             IF QOMX=QOLT, ZZ=NOB+PJ.
C
C                 QO(N)     - OBSERVES DISCHARGE ARRAY AS COMPUTED IN
C                             INTERP.
C
C                 MPT       - TIME OF THE SIMULATED PEAK, AS COMPUTED IN
C                             TOLER.
C
C                 EX2       - EXPONENT USED IN COMPUTING WEIGHT WD.
C
C       SUBROUTINE OUTPUT -
C
C                 OF        - THE OBJECTIVE FUNCTION
C
C***********************************************************************
C***********************************************************************
      DIMENSION QS(53),WD(53),WM(53),WT(53),DQ(53),SO(53),SS(53)
      COMMON/ALL/NOB,TILT,QOLT,PJ,QO(53),QOMX,ZZ,MPT
      COMMON/MAOBJ/EX2
C
      IN=0
C
```

```
C         COMPUTE THE SLOPE AT EACH OBSERVED DISCHARGE
C         SO(1)--SO(NOB) AND AT EACH SIMULATED DISCHARGE
C         ORDINATE SS(1)--SS(NOB+2)
C
C         COMPUTE SLOPES BASED ON VALUES OF ORDINATE
C         AT TIME L AND AT PRECEDING AND SUCCEEDING ORDINATES.
C         LAST SEGMENT USES ONLY PRECEDING ORDINATE.
C
      IF(NOB.NE.1) GO TO 2
      QO(2)=QOLT
      QO(3)=QOLT
 2    IF(NOB.NE.2) GO TO 3
      QO(3)=QOLT
 3    SO(1)=(QO(2)-QO(1))*.5
      SS(1)=(QS(2)-QS(1))*.5
      J=NOB-1
      IF(J.LT.1) J=1
      DO 4 L=2,J
      SO(L)=(QO(L+1)-QO(L-1))*0.5
 4    SS(L)=(QS(L+1)-QS(L-1))*0.5
      SO(NOB)=(QO(NOB)-QO(J))
      J=NOB+3
      DO 8 L=NOB,J
      XS=QS(1)
      IF(L.NE.1) XS=QS(L-1)
 8    SS(L)=QS(L)-XS
      IF(TILT.LT. 0.05) GO TO 9
      XO=QO(1)
      XS=QS(1)
      IF(NOB.EQ.1) GO TO 11
      XO=QO(NOB-1)
      XS=QS(NOB-1)
 11   SO(NOB)=(QO(NOB)*(PJ*PJ-1.)-XO*PJ*PJ+QOLT)/(PJ*(PJ+1.))
      SS(NOB)=(QS(NOB+1)-XS)*.5
      SOLT=(QOLT-QO(NOB))/PJ
C
C         COMPUTE THE OBJECTIVE FUNCTION TERMS FOR
C         ORDINATE NOS. 1 TO NOB.
C
 9    RMS=0.
      DO 44 L=1,NOB
C
C         COMPUTE THE DIFFERENCE BETWEEN SIMULATED AND  OBSERVED
C         DISCHARGES  AT EACH ORDINATE DQ(1)--DQ(NOB)
C
      DQ(L)=ABS(QO(L)-QS(L))
      RMS=RMS+DQ(L)*DQ(L)
C
C         COMPUTE TIMING WEIGHTS WT(1)--WT(NOB)
C
C         DT IS THE TIME OF OCCURRENCE OF A SIMULATED
C         DISCHARGE EQUAL TO THE OBSERVED DISCHARGE
C         AT ORDINATE L.
C
C         IF DT .LE. 3 HOURS, WT=0
C         IF DT .GT. 12 HOURS, WT=1
C         IF DT .GT. 3 HOURS BUT .LE. 12HOURS, WT RANGES
C             LINEARLY FROM 0 TO 1.
```

```
C
      Q=QO(L)
      DT=12.
 10   DO 24 J=1,4
      K=L+J-3
      KK=K+1
      KKK=K+2
      IF(K.LT.1) K=1
      IF(KK.LT.1) KK=1
      IF(KKK.LT.1) KKK=1
      AA=QS(K)
      AB=QS(KK)
      IF(IN.EQ.0) GO TO 12
      AA=AA+PJ*(AB-AA)
      AB=AB+PJ*(QS(KKK)-AB)
 12   S=SO(L)
      IF(IN.EQ.1) S=SOLT
      S=S*(AB-AA)
      IF(S.LT.0.) GO TO 24
      IF((ABS(Q-AA).LT..0001).AND.(ABS(Q-AB).LT..0001)) GO TO 18
      IF((ABS(AA-AB)).LT..0001) GO TO 24
      IF(Q-AA)14,20,16
 14   IF(Q-AB)24,20,20
 16   IF(Q-AB)20,20,24
 18   DEL=18.-15.*J+3.*J*J
      GO TO 22
 20   DEL=ABS(18.-6.*J-6.*(Q-AA)/(AB-AA))
 22   IF(DEL.LT.DT) DT=DEL
 24   CONTINUE
      WT(L)=(DT-3.)/9.
      IF(WT(L).LT.0.) WT(L)=0.
      IF(IN.EQ.1) GO TO 48
C
C              COMPUTE SLOPE WEIGHTS WM(1)--WM(NOB)
C
C              STE IS THE TIME OF OCCURRENCE OF THE NEAREST
C              SLOPE ON THE SIMULATED GRAPH EQUAL IN MAGNITUDE
C              TO THE SLOPE OF THE OBSERVED GRAPH AT ORDINATE L.
C
C              IF STE .LE. 3 HOURS, WM=0
C              IF STE .GT. 12 HOURS, WM=1
C              IF STE .GT. 3 HOURS BUT .LE. 12 HOURS, WM RANGES
C                  LINEARLY FROM 0 TO 1.
C
 26   AO=SO(L)
      STE=12.
 28   DO 42 J=1,4
      K=L+J-3
      KK=K+1
      KKK=K+2
      IF(K.LT.1) K=1
      IF(KK.LT.1) KK=1
      IF(KKK.LT.1) KKK=1
      AA=SS(K)
      AB=SS(KK)
      IF(IN.EQ.0.) GO TO 30
      AA=AA+PJ*(AB-AA)
      AB=AB+PJ*(SS(KKK)-AB)
```

```
 30   IF((ABS(AO-AA).LT..0001).AND.(ABS(AO-AB).LT..0001)) GO TO 36
      IF((ABS(AA-AB)).LT..0001) GO TO 42
      IF(AO-AA) 32,38,34
 32   IF(AO-AB)42,38,38
 34   IF(AO-AB)38,38,42
 36   DEL=18.-15.*J+3.*J*J
      GO TO 40
 38   DEL=ABS(18.-6.*J-6.*(AO-AA)/(AB-AA))
 40   IF(DEL.LT.STE)STE=DEL
 42   CONTINUE
      SWT=(STE-3.)/9.
      IF(SWT.LT.0.)SWT=0.
      IF(IN.EQ.1) GO TO 50
      WM(L)=ABS((SO(L)-SS(L))/QO(L))
      IF(WM(L).GT.1.0)WM(L)=1.0
      WM(L)=WM(L)*SWT
C
C           COMPUTE DISTANCE WEIGHTS WD(1)--WD(NOB) WHICH ARE BASED ON
C           THE TIME DISTANCE BETWEEN ORDINATE L AND THE
C           MAXIMUM OBSERVED DISCHARGE(QOMX). IF L IS GREATER
C           THAN THE TIME OF QOMX--(ZZ), THEN WD(L)=1.
C
      WD(L)=(L/ZZ)**EX2
      IF(WD(L).GT.1.0)WD(L)=1.0
 44   CONTINUE
C
C           COMPUTE THE PORTION OF THE OBJECTIVE FUNCTION
C           UP TO THE TIME OF ORDINATE NOB.
C
      WSUM=0.
      PRSUM=0.
      DO 46 L=1,NOB
      PRSUM=PRSUM+WD(L)*((WT(L)*DQ(L)+WM(L)*QO(L))/2.)
 46   WSUM=WSUM+WD(L)
      OF=PRSUM/WSUM
      IF(TILT.LT.0.05) GO TO 52
C
C           IF THE LAST OBSERVATION FALLS BETWEEN SIX-HOUR ORDINATES,
C           ADJUST THE FUNCTION FOR THE FRACTIONAL CONTRIBUTION.
C
      DT=12.
      Q=QOLT
      L=NOB
      IN=1
      GO TO 10
 48   WTLT=WT(L)
      DQLT=ABS(QOLT-QS(NOB)-PJ*(QS(NOB+1)-QS(NOB)))
      RMS=RMS+DQLT*DQLT*PJ
      STE=12.
      AO=SOLT
      GO TO 28
 50   WMLT=ABS((SOLT-SS(NOB)-PJ*(SS(NOB+1)-SS(NOB)))/QOLT)
      IF(WMLT.GT.1.0)WMLT=1.
      WMLT=WMLT*SWT
      PRSUM=PRSUM+PJ*(WTLT*DQLT+WMLT*QOLT)/2.
      OF=PRSUM/(WSUM+PJ)
 52   RMS=(SQRT(RMS/(PJ+NOB)))/4.
      WF=2.-(PJ+NOB)/MPT
```

```
      IF(WF.GT.1.) GO TO 53
      IF(WF.LT.0.) WF=0.
      OF=OF*WF+RMS*(1.-WF)
53    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE STRAT(NFORC,RH,RV,UG6,PP,QADJ)
C***********************************************************************
C***********************************************************************
C
C           THIS SUBROUTINE MAKES THE ADJUSTMENTS TO THE PRECIP
C           AND TO THE UNIT GRAPH(THROUGH SUBROUTINE WARP) ON
C           SUCCESSIVE PASSES. A RETURN IS MADE FROM THE SUBROUTINE
C           WHEN ONE OF 3 CONDITIONS EXIST: THE VALUE OF THE OBJECTIVE
C           FUNCTION IS LESS THAN THE TOLERANCE, NO IMPROVEMENTS WERE
C           MADE DURING A PASS, OR THE NUMBER OF PASSES ALLOWED HAS
C           BEEN EXCEEDED. THE SUBROUTINE RETURNS THE ADJUSTED SET
C           OF PRECIP AND UNIT GRAPH VALUES AND THE CORRESPONDING
C           ADJUSTED HYDROGRAPH.
C
C     SUBROUTINE INPUT --
C
C           NFORC     - THE CURRENT SIX-HOUR PERIOD, NUMBERED
C                       SEQUENTIALLY FROM THE BEGINNING OF THE
C                       RUNOFF EVENT
C
C           TOL       - THE TOLERANCE
C
C           NJ        - =0 ORIGINAL SIMULATION SATISFACTORY,NO ADJUST-
C                          MENTS NECESSARY. SUBROUTINE USED ONLY FOR
C                          COMPUTING CONSTRAINTS ON LATEST(NFORC)
C                          PRECIP VALUE.
C                       =1 COMPUTE CONSTRAINTS AND BEGIN ADJUSTMENTS
C
C           UGI2(107)   ORIGINAL UNIT GRAPH, ORDINATES SPACED EVERY
C                       2 HOURS, BEGINNING AND ENDING WITH ZERO(TO BE
C                       PASSED ON TO WARP)
C
C
C           MAXN      - MAXIMUM NUMBER OF PASSES ALLOWED THROUGH THE
C                       ADJUSTMENT STRATEGY.
C
C           DEL       - DELTA APPLIED TO PRECIP
C           WDEL      - DELTA APPLIED TO RH AND RV
C           WHL       - LOWER CONSTRAINT ON RH
C           WHH       - UPPER CONSTRAINT ON RH
C           WVL       - LOWER CONSTRAINT ON RV
C           WVH       - UPPER CONSTRAINT ON RV
C
C           ZLOW      - THE CONSTANT MULTIPLIER FOR THE LOWER
C                       PRECIP CONSTRAINT.
C
C           HIGH      - THE CONSTANT MULTIPLIER FOR THE UPPER
C                       PRECIP CONSTRAINT.
C
C           UCX       - THE 'FIXED' UPPER PRECIP CONSTRAINT.
C
C           RH        - HORIZONTAL WARP COEFFICIENT AT END
C                       OF PREVIOUS FORECAST TIME
C
C           RV        - VERTICAL WARP COEFFICIENT AT END OF
C                       PREVIOUS FORECAST TIME
C
C           UG6(36)   - WARPED UNIT GRAPH(ORDINATES SPACED
```

```
C                       EVERY 6 HOURS) RESULTING FROM THE
C                       ABOVE RH AND RV VALUES
C
C             PP(53)  - PRECIP VALUES 1 THRU (NFORC-1), AS
C                       ADJUSTED DURING PREVIOUS FORECAST
C                       TIME PLUS CURRENT REPORTED VALUE,PP(NFORC)
C
C             OFB     - OBJECTIVE FUNCTION FOR THE BASE SIM-
C                       ULATION AT TIME NFORC, WHICH USES THE
C                       PRECIP AND UNIT GRAPH ARRAYS DESCRIBED
C                       ABOVE
C
C
C     SUBROUTINE OUTPUT --
C
C             RH      - THE ADJUSTED HORIZONTAL WARP COEFFICIENT
C             RV      - THE ADJUSTED VERTICAL WARP COEFFICIENT
C
C             UG6(36) - WARPED UNIT GRAPH(ORDINATES SPACED
C                       EVERY 6 HOURS) RESULTING FROM THE
C                       ABOVE RH AND RV VALUES
C
C             PP(53)  - THE ADJUSTED PRECIP VALUES, 1 THRU NFORC
C
C             QADJ(53) - THE ADJUSTED HYDROGRAPH RESULTING FROM
C                       THE PRECIP AND UNIT GRAPH ARRAYS
C                       DESCRIBED ABOVE
C
C             OFB     - THE OBJECTIVE FUNCTION FOR THE ADJUSTED
C                       HYDROGRAPH
C
C             MSG     - INDICATES WHICH EXIT CONDITION WAS USED-
C                       =1 NO IMPROVEMENTS WERE MADE ON LAST PASS
C                       =2 OBJECTIVE FUNCTION IS LESS THAN TOLERANCE
C                       =3 NUMBER OF PASSES HAS BEEN EXCEEDED
C***********************************************************************
C
C***********************************************************************
      REAL LK,MXIMP
      DIMENSION PP(53),UG6(36),QADJ(53)
      COMMON/STWARP/ IZZ
      COMMON/MASTRA/UGI2(107),OFB,MAXN,DEL,WDEL,WHL,WHH,
     1   WVL,WVH,ZLOW,HIGH,UCX,TOL,MSG,NJ,SUM,LK(53),UK(53)
C
C             COMPUTE CONSTRAINT ON PRECIP VALUE OF NFORC
C
      IF(NFORC.EQ.1) SUM=0.
      UK(NFORC)=HIGH*PP(NFORC)
      LK(NFORC)=ZLOW*PP(NFORC)
      SUM=SUM+PP(NFORC)
      UMN=.2*SUM
      IF(UMN.LT.UCX)UMN=UCX
      IF(UK(NFORC).LT.UMN) UK(NFORC)=UMN
      IF(NJ.EQ.0) RETURN
C
      IPASS=1
C
C             BEGIN PASS
```

```
C
C               APPLY A  + AND - DELTA TO EACH PRECIP VALUE,ONE AT
C               A TIME. COMPUTE CRITERION FOR EACH ADJUSTMENT.
C
      IST=0
 5    MSG=0
      MXIMP=0.
      DO 10 I=1,NFORC
      ICON=0
      PP(I)=PP(I)+DEL
      IF(PP(I).LE.UK(I)) GO TO 8
      ICON=1
      P=PP(I)
      PP(I)=UK(I)
 8    CALL MODEL(PP,UG6,QADJ)
      CALL OBJEC(NFORC,QADJ,OF)
      CHNG=OFB-OF
      IF(CHNG.LE.MXIMP) GO TO 20
      MXIMP=CHNG
      CPR=I
      BP=PP(I)
      IF(ICON.EQ.1) PP(I)=P
      PP(I)=PP(I)-DEL
      GO TO 10
 20   IF(ICON.EQ.1)PP(I)=P
      ICON=0
      PP(I)=PP(I)-2.*DEL
      IF(PP(I).GE.LK(I)) GO TO 12
      ICON=1
      P=PP(I)
      PP(I)=LK(I)
 12   CALL MODEL(PP,UG6,QADJ)
      CALL OBJEC(NFORC,QADJ,OF)
      CHNG=OFB-OF
      IF(CHNG.LE.MXIMP) GO TO 15
      MXIMP=CHNG
      CPR=I
      BP=PP(I)
 15   IF(ICON.EQ.1)PP(I)=P
      PP(I)=PP(I)+DEL
 10   CONTINUE
C
C               COMPUTE SENSITIVITY TERM ONCE FROM THE FIRST MAXIMUM
C               IMPROVEMENT. FINALIZE THE IMPROVEMENT WHICH MOST
C               IMPROVED THE CRI!ERION(ONLY IF THE IMPROVEMENT IS
C               SIGNIFICANT,I.E.¯75% OF THE SENSITIVITY)
C
      IF(MXIMP.LE.0.) GO TO 50
      IF(IST.EQ.1) GO TO 30
      IST=1
      OFBSE=OFB
      STY=.075*(MXIMP/OFB)
C
 30   IF((MXIMP/OFBSE).LT.STY) GO TO 40
      PP(CPR)=BP
      CALL MODEL(PP,UG6,QADJ)
      CALL OBJEC(NFORC,QADJ,OF)
      OFB=OF
      GO TO 50
```

```
   40 MXIMP=0.
C
C            ADJUST UNIT GRAPH
C
   50 IG=0
      LCON=0
      KCON=0
      RV=RV+WDEL
      IF(RV.LT.WVH) GO TO 52
      LCON=1
      CALL WARP(RH,WVH,UGI2,UG6)
      GO TO 53
   52 CALL WARP(RH,RV,UGI2,UG6)
   53 IF(IZZ.NE.1) GO TO 54
      IZZ=0
      GO TO 60
   54 CALL MODEL(PP,UG6,QADJ)
      CALL OBJEC(NFORC,QADJ,OF)
      IF(OF.GE.OFB) GO TO 60
      OFB=OF
      IG=1
      IF(LCON.EQ.1) RV=WVH
      GO TO 70
   60 RV=RV-2.*WDEL
      IF(RV.GT.WVL) GO TO 62
      KCON=1
      CALL WARP(RH,WVL,UGI2,UG6)
      GO TO 63
   62 CALL WARP(RH,RV,UGI2,UG6)
   63 IF(IZZ.NE.1) GO TO 64
      IZZ=0
      GO TO 65
   64 CALL MODEL(PP,UG6,QADJ)
      CALL OBJEC(NFORC,QADJ,OF)
      IF(OF.GE.OFB) GO TO 65
      OFB=OF
      IG=1
      IF(KCON.EQ.1)RV=WVL
      GO TO 70
   65 RV=RV+WDEL
C
   70 LCON=0
      KCON=0
      RH=RH+WDEL
      IF(RH.LT.WHH) GO TO 72
      LCON=1
      CALL WARP(WHH,RV,UGI2,UG6)
      GO TO 73
   72 CALL WARP(RH,RV,UGI2,UG6)
   73 IF(IZZ.NE.1) GO TO 74
      IZZ=0
      GO TO 80
   74 CALL MODEL(PP,UG6,QADJ)
      CALL OBJEC(NFORC,QADJ,OF)
      IF(OF.GE.OFB) GO TO 80
      OFB=OF
      IG=1
      IF(LCON.EQ.1) RH=WHH
```

```
      GO TO 90
 80   RH=RH-2.*WDEL
      IF(RH.GT.WHL) GO TO 82
      KCON=1
      CALL WARP(WHL,RV,UGI2,UG6)
      GO TO 83
 82   CALL WARP(RH,RV,UGI2,UG6)
 83   IF(IZZ.NE.1) GO TO 84
      IZZ=0
      GO TO 85
 84   CALL MODEL(PP,UG6,QADJ)
      CALL OBJEC(NFORC,QADJ,OF)
      IF(OF.GE.OFB) GO TO 85
      OFB=OF
      IG=1
      IF(KCON.EQ.1) RH=WHL
      GO TO 90
 85   RH=RH+WDEL
C
C                 PASS COMPLETE
C
C                 IF NO PERTURBATIONS IMPROVED CRITERION, RETURN.
C                 IF A PERTURBATION IMPROVED CRITERION TO AN ACCEPTABLE
C                 TOLERANCE, RETURN.
C                 OTHERWISE, CONTINUE OPTIMIZATION WITH ANOTHER PASS,
C                 IF NUMBER OF PASSES HAS NOT EXCEEDED THE LIMIT.
C
 90   IF((MXIMP.LE.0.).AND.(IG.EQ.0)) MSG=1
      IF(OFB.LE.TOL) MSG=2
      CALL WARP(RH,RV,UGI2,UG6)
      IF(MSG.GE.1) GO TO 110
      IF(IPASS.EQ.MAXN) GO TO 100
      IPASS=IPASS+1
      GO TO 5
C
 100  MSG=3
 110  CALL MODEL(PP,UG6,QADJ)
      RETURN
      END
```

```
      SUBROUTINE WARP(RH,RV,UGI,UG6)
C***********************************************************************
C***********************************************************************
C
C                 THIS SUBROUTINE ALTERS(WARPS) THE UNIT GRAPH
C                 ACCORDING TO THE VALUES ASSIGNED TO THE HORIZONTAL
C                 WARP COEFFICIENT RH AND THE VERTICAL WARP
C                 COEFFICIENT RV
C
C     SUBROUTINE INPUT -
C
C                 RH         - HORIZONTAL WARP COEFFICIENT.
C                 RV         - VERTICAL WARP COEFFICIENT.
C
C                 UGI(107)   - UNIT GRAPH TO BE WARPED. ORDINATES EVERY
C                              TWO HOURS, BEGINNING AND ENDING WITH ZERO.
C
C     SUBROUTINE OUTPUT -
C
C                 UG6(36)    - WARPED UNIT GRAPH,ORDINATES SPACED EVERY
C                              SIX HOURS, BEGINNING WITH FIRST NON-ZERO VALUE.
C
C                 IZZ        - PASSED BACK TO STRAT WHERE IT IS INTERRO-
C                              GATED TO SEE IF COMPLEX ROOTS ENCOUNTERED.
C
C***********************************************************************
C***********************************************************************
C
      DIMENSION UG(107),UGI(107),C(106),UG6(36)
      COMMON/STWARP/ IZZ
C
      UGI(107)=0.
      DO 50 I=1,107
 50   UG(I)=UGI(I)
C
C     COMPUTE RO VOLUME, GRO AND HORIZONTAL SHIFT, SHFT.
C
      GRO=0.
      QMAX=0.
      DO 1 K=1,107
      GRO=GRO+UG(K)
      IF(UG(K).LE.QMAX) GO TO 1
      J=K
      QMAX=UG(K)
    1 CONTINUE
      GPT=2*(J-1)
      SHFT=RH*GPT-GPT
C
C     SHIFT HYDROGRAPH RIGHT OR LEFT
C
      IF(SHFT)2,13,8
    2 SHFT=SHFT*(-1.)
    3 IF(SHFT-2.)6,4,4
    4 DO 5 K=1,106
    5 UG(K)=UG(K+1)
      UG(107)=0.
      SHFT=SHFT-2.
      GO TO 3
```

```
    6 SHFT=SHFT*.5
      DO 7 K=1,106
    7 UG(K)=UG(K)+SHFT*(UG(K+1)-UG(K))
      UG(1)=0.
      UG(107)=0.
      GO TO 13
    8 IF(SHFT-2.)11,9,9
    9 DO 10 K=1,106
      J=108-K
   10 UG(J)=UG(J-1)
      UG(1)=0.
      SHFT=SHFT-2.
      GO TO 8
   11 SHFT=SHFT*.5
      DO 12 K=1,106
      J=108-K
   12 UG(J)=UG(J)+SHFT*(UG(J-1)-UG(J))
C
C     WARP HYDROGRAPH VERTICALLY.
C     COMPUTE CURVATURE, C(K).
C
   13 QMAX=0.
      UG(1)=0.
      UG(106)=0.0
      UG(107)=0.
      DO 14 K=1,106
      IF(UG(K).GT.QMAX)QMAX=UG(K)
      X=0.
      IF(K.GT.1)X=UG(K-1)
      Y=X+UG(K+1)
      C(K)=0.
      IF(Y.EQ.0.)GO TO 14
      C(K)=2.*UG(K)/Y
   14 CONTINUE
      IF((RV.LT. .999).OR.(RV.GT.1.0001)) GO TO 16
      DO 15 K=1,106
   15 C(K)=1.
      B=1.
      GO TO 26
C
C     LOCATE INFLECTION POINTS.
C
   16 NT=0
      X=0
      QMAX=QMAX*.2
      DO 21 K=2,106
      IF(UG(K).LT.QMAX) GO TO 21
      IF(C(K)-1.)17,19,20
   17 IF(C(K+1).LT.1.)GO TO 21
   18 NT=NT+1
      X=X+UG(K)+(UG(K+1)-UG(K))*(1.-C(K))/(C(K+1)-C(K))
      GO TO 21
   19 NT=NT+1
      X=X+UG(K)
      GO TO 21
   20 IF(C(K+1)-1.)18,21,21
   21 CONTINUE
      Y=NT
```

```
      X=Y/X
C
C     X IS AVERAGE OF ALL INFLECTION POINT DISCHARGES. RE-COMPUTE C(K)
C     AS A LINEAR FUNCTION OF DISCHARGE SO THAT WHEN UG=0, C(K)=0 AND
C     WHEN UG=X, C(K)=1.
C
      DO 22 K=1,106
   22 C(K)=UG(K)*X
C
C     VERTICAL WARP EQUATION IS - Q(K)=Q(K)*RV*((1.+A*(1.-C(K)))/RV)**B
C     COMPUTE COEFFICIENT. A.
      CMX=QMAX*X*5.
      ATS=(RV-1.)/(1.-CMX)
      DO 23 K=1,106
      C(K)=(1.+ATS*(1.-C(K)))/RV
      IF(C(K).LT.0.)C(K)=0.
   23 CONTINUE
C
C     BY ITERATION, DETERMINE A VALUE FOR THE EXPONENT, B, WHICH WILL
C     CAUSE THE VOLUME OF THE ADJUSTED HYDROGRAPH TO BE EQUAL TO GRO.
C
      BA=0.
      RA=RV
      NT=0
      IZZ=0
      GO TO 38
   24 X=0.
      DO 25 K=1,106
   25 X=X+UG(K)*RV*(C(K))**B
      R=X/GRO
      GO TO (30,31,34,35),J
   38 BB=1.
      B=1.
      J=1
      GO TO 24
   30 RB=R
      BC=2.
      B=2.
      J=2
      GO TO 24
   31 RC=R
   37 NT=NT+1
      Z1=RC-RB
      Z2=BA-BB
      Z3=RA-RB
      Z4=BC-BB
      Z5=BC*BC-BB*BB
      Z6=BA*BA-BB*BB
      ZC=(Z1*Z2-Z3*Z4)/(Z5*Z2-Z6*Z4)
      ZB=(Z1-ZC*Z5)/Z4
      ZA=RA-ZB*BA-ZC*BA*BA-1.
      Z7=ZB*ZB-4.*ZC*ZA
      IF(Z7)32,33,33
   32 PRINT 40
   40 FORMAT(17HROOTS ARE COMPLEX)
      IZZ=1
      RETURN
   33 Z7=SQRT(Z7)
```

```
      R1=(-ZB-Z7)/(2.*ZC)
      R2=(Z7-ZB)/(2.*ZC)
      J=3
      B=R1
      GO TO 24
   34 TR1=R
      J=4
      B=R2
      GO TO 24
   35 TR2=R
      IF(ABS(TR1-1.).GT.ABS(TR2-1.))GO TO 36
      B=R1
      R=TR1
   36 IF(NT.GT.15)GO TO 26
      ER=ABS(R-1.)
      IF(ER.LT..01)GO TO 26
      RA=RB
      RB=RC
      RC=R
      BA=BB
      BB=BC
      BC=B
      GO TO 37
C
C     COMPUTE ADJUSTED HYDROGRAPH
C
  26  DO 27 K=1,35
      J=3*K+1
 27   UG6(K)=UG(J)*RV*(C(J))**B
      UG6(36)=0.
      RETURN
      END
```

```
      SUBROUTINE BLEND(QS)
C***********************************************************************
C***********************************************************************
C
C             THIS SUBROUTINE RESOLVES THE MINOR REMAINING DIFFERENCE
C             BETWEEN THE FINAL ADJUSTED SIMULATION AND THE OBSERVED
C             DISCHARGE BY BLENDING.
C
C     SUBROUTINE INPUT -
C
C             QS(53)   - THE ARRAY OF ADJUSTED 6-HOUR SIMULATED
C                        DISCHARGES.
C             NOB,GOLT,PJ,QO(N)   -  AS COMPUTED IN INTERP AND
C                                    DEFINED IN OBJEC.
C
C     SUBROUTINE OUTPUT -
C
C             QBL(53)  - THE BLENDED HYDROGRAPH, WHICH IS THE FORECAST
C
C***********************************************************************
C***********************************************************************
C
      DIMENSION QS(53)
      COMMON/BLOT/QBL(53)
      COMMON/ALL/NOB,TILT,QOLT,PJ,QO(53),QOMX
C
      DO 10 K=1,NOB
 10   QBL(K)=QO(K)
      DELQ=QOLT-QS(NOB)-PJ*(QS(NOB+1)-QS(NOB))
      L=NOB+1
      M=NOB+6
      DO 20 K=L,M
 20   QBL(K)=QS(K)+(DELQ/6.)*(M-K+PJ)
      L=NOB+7
      DO 30 K=L,53
 30   QBL(K)=QS(K)
      RETURN
      END
```

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(Continued from inside front cover)

WS HYDRO 16 A Dynamic Model of Stage-Discharge Relations Affected by Changing Discharge. D. L. Fread, November 1973 (revised, October 1976), 38 pp. plus appendixes A and B. (COM-74-10818)

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WS HYDRO 21 Storm Tide Frequency Analysis for the Coast of North Carolina, South of Cape Lookout. Francis P. Ho and Robert J. Tracey, May 1975, 44 pp. (COM-75-11000/AS)

S HYDRO 22 Annotated Bibliography of NOAA Publications of Hydrometeorological Interest. John F. Miller, May 1975, 50 pp. (Superseded by NWS HYDRO 34)

S HYDRO 23 Storm Tide Frequency Analysis for the Coast of Puerto Rico. Francis P. Ho, May 1975, 43 pp. (COM-11001/AS)

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S HYDRO 32 Storm Tide Frequency Analysis for the Open Coast of Virginia, Maryland, and Delaware. Francis P. Ho, Robert J. Tracey, Vance A. Myers, and Normalee S. Foat, August 1976, 52 pp. (PB261969)

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S HYDRO 36 Determination of Flood Forecast Effectiveness by the Use of Mean Forecast Lead Time. Walter T. Sittner, August 1977, 22 pp.

S HYDRO 37 Derivation of Initial Soil Moisture Accounting Parameters From Soil Propertiess for the National Weather Service River Forecast System. Bobby L. Armstrong, March 1978, 53 pp. (PB-280-710)

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