Section 7-6

Unit Hydrograph Application for the Sacramento Model

Introduction

A number of methods could be used to convert runoff generated by a rainfall-runoff model into a discharge hydrograph at a location on the channel system. The only current method included in NWSRFS is the unit hydrograph procedure. This section describes how a unit hydrograph should be applied with the Sacramento model and methods for determining an initial estimate of the unit hydrograph for a drainage area. Also discussed are items to consider when using a unit hydrograph including the time interval of the ordinates, application to watersheds that are divided into multiple zones, and how to handle watersheds where the shape of the response varies considerably depending on the flow level.

Function of a Unit Hydrograph for Use with the Sacramento Model

The Sacramento model generates runoff into the channel system. Delays that occur as water moves through the soil, either as interflow or baseflow, are accounted for within the model. Time delays associated with surface and impervious runoff are not included in the Sacramento model as these runoff components are added to the channel runoff during the same period as the rain or melt occurs. Thus, when a unit hydrograph is used with the Sacramento model, the unit hydrograph must account for the delay and attenuation that occurs as surface and impervious runoff moves over the land surface and, most importantly, the delay and attenuation that occurs as the water moves through the channel system. Typically the response time of the channel system is much more significant than the overland flow response time and thus dominates the unit hydrograph.

In more traditional applications of the unit hydrograph method, such as with an API type rainfall-runoff model, the procedure must account for storm runoff delays both through and over the soil, as well as the effect of the channel system on watershed response. For a watershed where surface runoff dominates storm events and there is very little interflow produced, the function of a traditional unit hydrograph is basically the same as the unit hydrograph that would be used with the Sacramento model. However, for a watershed where interflow, or possibly even supplemental baseflow, is a major contributor to storm runoff, the delay time for the water moving through the soil needs to be included in the unit hydrograph and thus a traditional unit hydrograph is not appropriate for use with the Sacramento model. Figure 7-6-1 shows a traditional, i.e. API model, unit hydrograph for a watershed that has a considerable interflow contribution during most storm events. The figure also shows the interflow component of the API unit hydrograph and the appropriate Sacramento model unit hydrograph for this watershed. The Sacramento model unit hydrograph is derived by subtracting the interflow component from the API unit hydrograph and adjusting the ordinates so that they add up to the correct sum.

Figure 7-6-1. Unit hydrographs for a watershed with considerable interflow.

When using the unit hydrograph method with an API model, the shape of the storm response is always the same no matter how much storm runoff is generated since the unit hydrograph is a linear function and the storm runoff is all applied to the same time interval when the rain or melt occurs. When the unit hydrograph is used with the Sacramento model, even though the unit hydrograph is a linear function, the watershed response is nonlinear because the breakdown of total storm runoff into interflow and surface runoff varies depending on the amount of rain, the rainfall intensity, and the soil moisture conditions. With the Sacramento model only the fast response runoff, i.e. surface and impervious, is all produced at one time. Interflow and baseflow contributions are made available to the unit hydrograph over a number of time intervals after the rain or melt occurs. Using the unit hydrographs shown in Figure 7-6-1, the next two figures illustrate how the Sacramento model response differs from an API model response for synthetic storm events of different magnitudes. Figure 7-6-2 shows a watershed response to various amounts of storm runoff when an API model is used. The shape of the response is the same for all three cases. Figure 7-6-3 shows the response of the watershed when using the Sacramento model for the same three events. The event with 8.15 mm of storm runoff only generates interflow, while the 21.23 mm event has 57% surface runoff and 43% interflow, and the 50.1 mm case is produced by 81% surface runoff and only 19% interflow. When comparing these two figures one can see that by using the unit hydrograph to model only the channel system and not interflow response with the Sacramento model, that small events can have a lower peak and more damped response, while large events will have a higher peak and quicker response than when using an API model with a unit hydrograph.

It is very important to clearly understand what the unit hydrograph is being used to represent when working with the Sacramento model. If unit hydrographs derived for use with an API model are to be used with the Sacramento model, any interflow or baseflow contribution must first be removed so that the resulting unit hydrograph only represents the delay and attenuation of water through the channel system and over the land surface.

Figure 7-6-2. API model response to different size storm events.

Figure 7-6-3. Sacramento model response to different size storm events.

Derivation of an Initial Unit Hydrograph for the Sacramento Model

There are two basic methods for deriving an initial estimate of the unit hydrograph for use with the Sacramento model. The first is to use data from actual storm events for the watershed and the second is to use one of a number of techniques to derive a synthetic unit hydrograph. If the proper conditions exist it is much better to derive the unit hydrograph using actual storm data.

Derivation of a Sacramento Model Unit Hydrograph from Storm Events

The procedure to derive a Sacramento model unit hydrograph from actual watershed data involves separating the fast response runoff contribution, i.e. surface and impervious, from the other runoff components prior to doing the unit hydrograph computations. In order to do this the following conditions must be met:

- the storms used must produce a significant amount of fast response runoff,
- there must be a reasonably clean recession period for some time after each event, typically in order of several weeks, and
- the precipitation causing the storm response should occur within a few time intervals; all within one period is best, but up to 3 or 4 time intervals are okay (complex storms and snowmelt periods should be avoided as when deriving a traditional unit hydrograph).

In order to separate out the fast response runoff contribution so that the effect of the channel system and overland flow can be isolated, a recession analysis is used. The recession analysis should allow one to remove the baseflow and interflow contribution. This is analogous to separating out baseflow when deriving a traditional unit hydrograph only in this case the interflow contribution must also be removed. Once the watershed response to surface and impervious runoff is determined, then the remainder of the process is exactly the same as when computing unit hydrograph ordinates in the traditional case. If one is not familiar with these steps, they are described in many textbooks.

In order to perform a recession analysis, a semi-log plot is generated for the receding portion of the hydrograph. Such a case is shown in Figure 7-6-4. This figure contains an idealized case generated with synthetic data so that the steps in the procedure can easily be described. The steps in the recession analysis are:

- Identify the primary baseflow component if possible. This component will plot as a straight line on the semi-log plot after interflow and supplemental baseflow storages have been drained completely. In the figure, the plot is not extended all the way out to this point. Extend the primary baseflow contribution back to under the peak of the hydrograph and then subtract the primary flow component from the total flow. The result is shown as ‘total - primary’ in the figure.

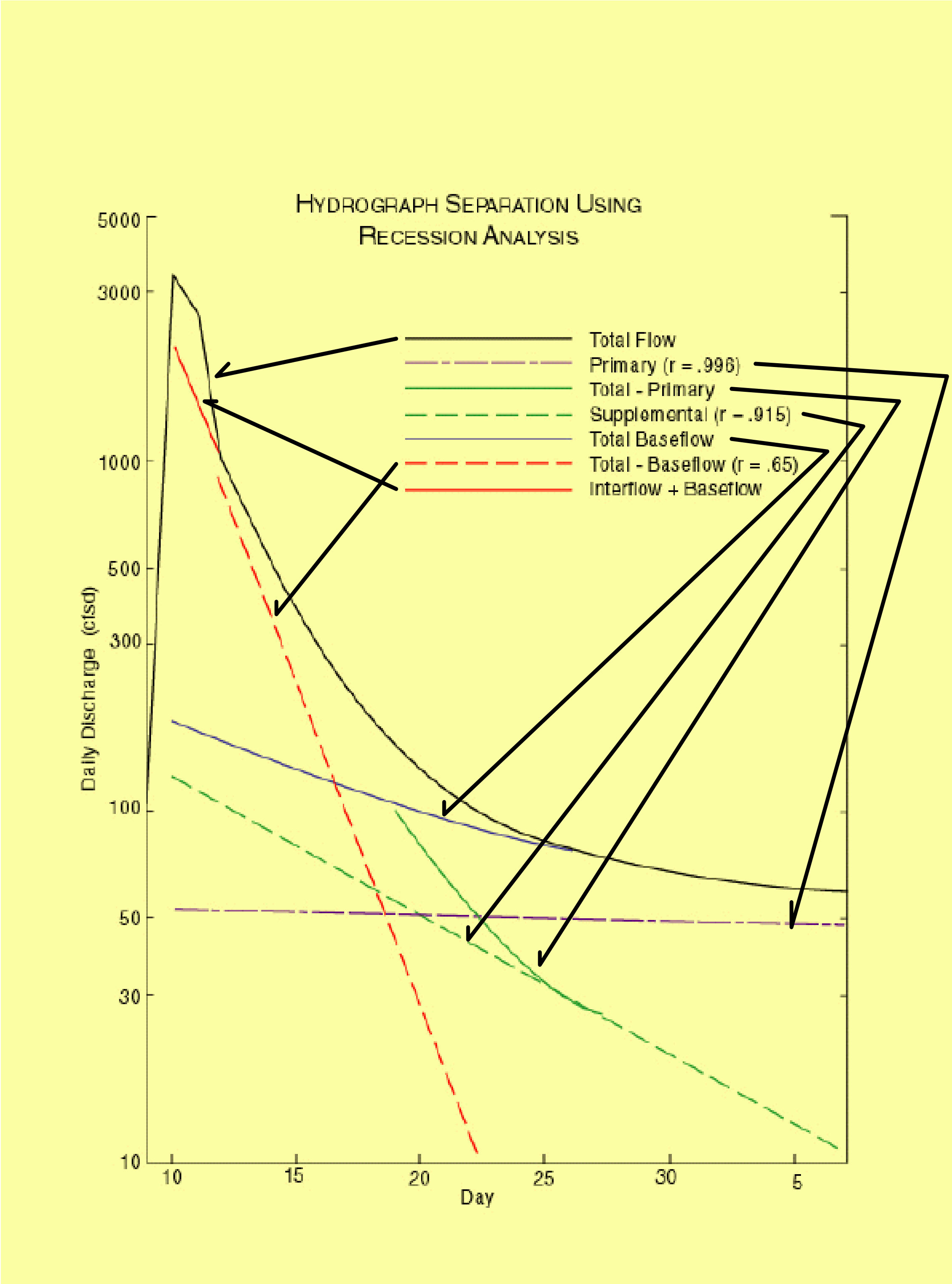

Figure 7-6-4. Illustration of a recession analysis using synthetic data.

- The straight line portion of the total minus primary line on the plot identifies the supplemental baseflow component. Extend the supplemental baseflow contribution back to under the hydrograph peak and then add the supplemental baseflow to the primary amount to get the total baseflow for this event. Then subtract the total baseflow from the total flow to get the 'total - baseflow' contribution. The total minus baseflow portion is shown on the plot starting at about the point where fast response runoff ceases though it could be extended back under the peak. In many real cases it is difficult to separate out primary and supplemental baseflow contributions, especially when the recession period is not very long or the supplemental withdrawal rate is quite slow. In these cases one would try to identify the total baseflow contribution, rather than dealing with primary and supplemental separately. The total baseflow recession will not plot exactly as a straight line on a semi-log plot since it is comprised of flow from two aquifers with different recession rates.

The 'total - baseflow' line will normally plot as a straight, or nearly straight, line on the semi-log plot. A recession rate can be computed for this segment. This is not the interflow recession rate, but instead an indication of how fast water is draining from the upper zone free water storage both as percolation and interflow. If soil moisture conditions are nearly saturated and this is a watershed with very low percolation rates under wet conditions, the amount of percolation should be small and thus, the total minus baseflow recession rate would be only slightly greater than the interflow recession rate and could be used to calculate an initial estimate of the Sacramento model UZK parameter. In most cases the 'total - baseflow' recession rate will be considerably greater than the interflow recession rate and can only be used as an extreme upper limit for UZK.

- The straight line portion of the 'total - baseflow' amount indicates the interflow contribution to the storm. This straight line segment is then extended back under the hydrograph peak and the total baseflow is added to the interflow contribution to obtain the amount of 'baseflow + interflow' for the event. This amount is only less than the total flow for a short time after the rain that produced the rise. During the remainder of the recession all the flow is either interflow or baseflow.

- The last step is to plot the total baseflow and the baseflow plus interflow amounts on an arithmetic plot as shown in Figure 7-6-5. Some subjectivity is needed when drawing the recharge portion , i.e. the period from when the hydrograph starts to rise until these flow components start to recede. The upper zone free water storage and thus interflow should typically peak a time interval or two after the storm peak, while baseflow recharge generally will take longer and thus, the baseflow contribution will not peak until a day or two after the storm peak.

The sum of interflow and baseflow can then be subtracted from the total instantaneous discharge amount to get the fast runoff, i.e. surface plus impervious, contribution to the storm. The surface plus impervious discharge is then used to derive the unit hydrograph . to be used with the Sacramento model using textbook methods.

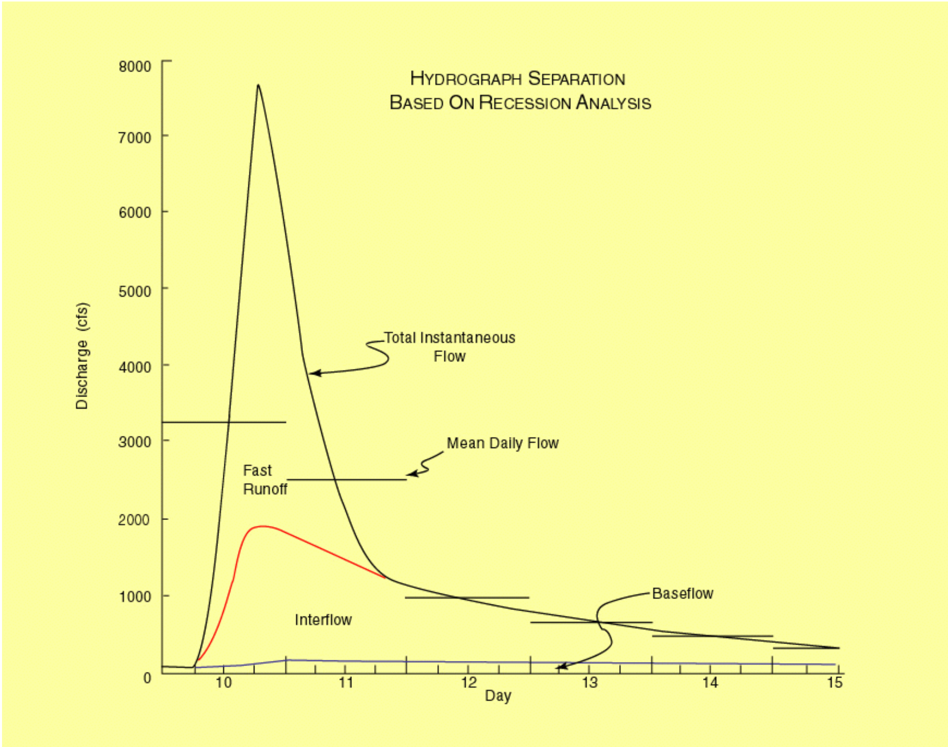

Figure 7-6-5. Separation of fast resonse runoff for deriving a unit hydrograph.

Figure 7-6-6 shows a recession analysis for an actual watershed. In this case there are several small events that occur in the period after the main storm, thus making it more difficult to determine the baseflow contribution. By looking at a low flow period further out in time than shown on the plot, the total baseflow contribution could be reasonably estimated. Then baseflow was subtracted from total flow to obtain the 'total - baseflow' amount and the straight portion of this line indicates the interflow contribution. 'Interflow + baseflow' was then computed and plotted for the storm event. Differences between total flow and 'interflow + baseflow' for the storm event that occur during the recession are the result of interflow and baseflow recharge from the subsequent small rainfall events. The total baseflow and 'interflow + baseflow' amounts are then plotted on an arithmetic plot as shown in Figure 7-6-7 to determine the fast runoff contribution to the storm hydrograph. Observed instantaneous discharge data were not available for this event so the total instantaneous flow was estimated by knowing the mean daily discharge amounts and the instantaneous peak flow. The rainfall for this event is also shown in the figure. The period of rain that generated most of the runoff was between 6 and 12 hours in length. Thus, the Sacramento model unit hydrograph computed from the fast runoff contribution to this event will be between a 6 and 12 hour unitgraph. An "S" curve analysis could be used to try and determine the appropriate time interval and then to compute a 6 hour unitgraph to be used with the model. If the storm event doesn't contain any fast response runoff, which was the case most of the time for the Ellijay watershed (surface runoff only occurs 3 times during the period of record), then the recession analysis should show that the entire rise is primarily from interflow and the event can't be used to determine an estimate of the unit hydrograph to use with the Sacramento model.

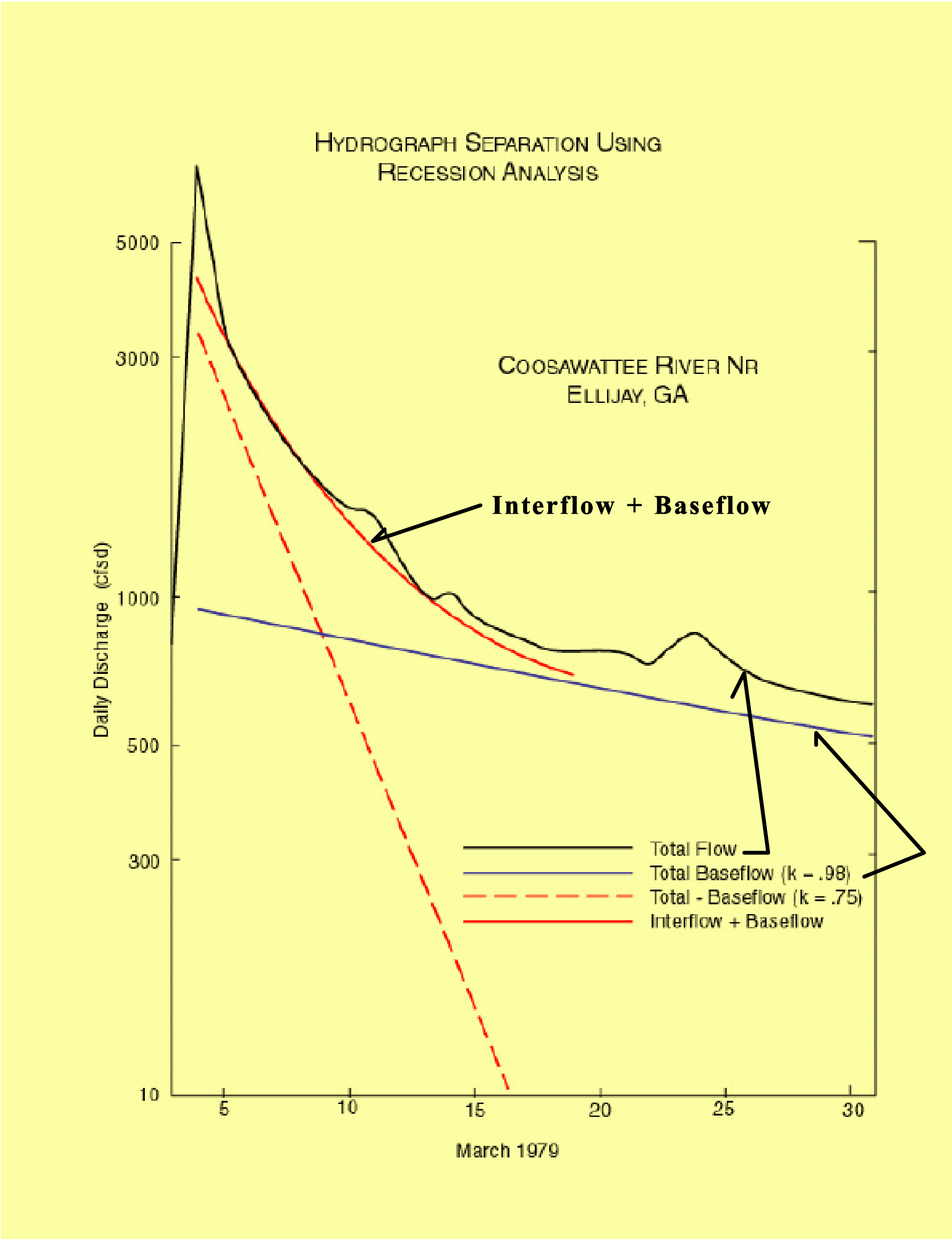
HYDROGRAPH SEPARATION USING
RECESSION ANALYSIS
COOSAWATTEE RIVER NR
ELLIJAY, GA
Interflow + Baseflow
Daily Discharge (cfsd)
5000
3000
1000
500
300
10
5
10
15
20
25
30
March 1979
Total Flow
Total Baseflow (k = .98)
Total - Baseflow (k = .75)
Interflow + Baseflow

Figure 7-6-6. Recession analysis for the Ellijay watershed for March 1979 storm.

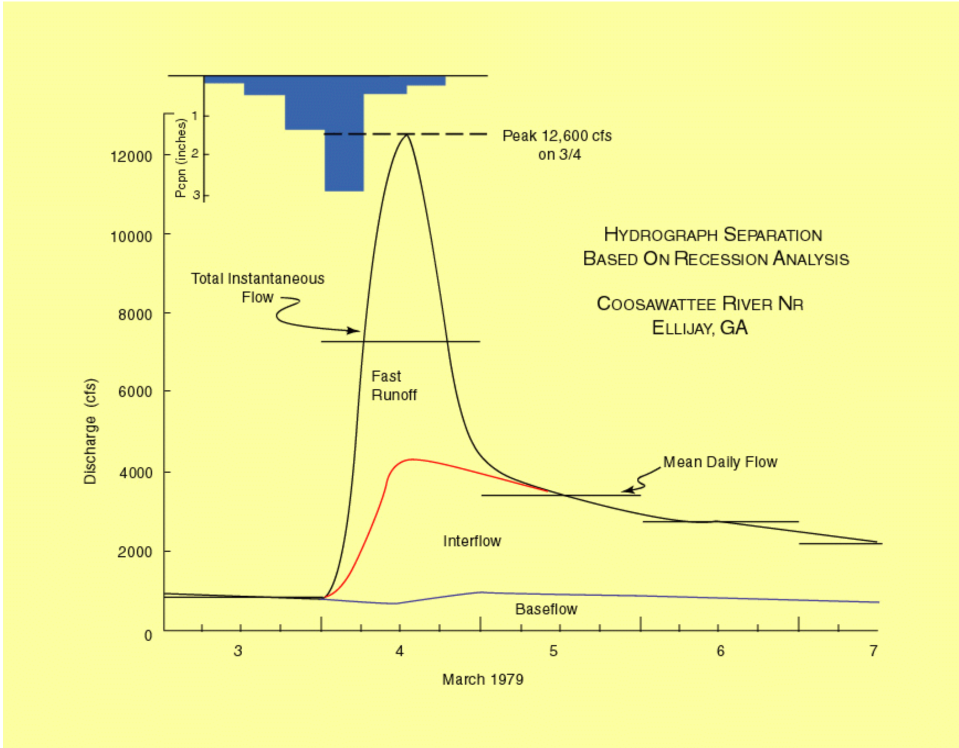

Figure 7-6-7. Fast runoff contribution to March 1979 storm for the Ellijay watershed.

<u>Derivation of an Initial Unit Hydrograph using Synthetic Methods</u>

If a unit hydrograph for use with the Sacramento model cannot be derived from precipitation and discharge data for the watershed, then there are a number of synthetic methods that have been proposed that are available. These methods generally fall into two categories. First there are time of travel methods which compute the portion of the watershed contributing each time interval based on travel time estimates. Second there are methods that use watershed geometry to estimate the peak discharge, the time to peak, and the base of the unit hydrograph. These methods contain coefficients that are determined from unit hydrographs derived from actual watershed data though in many cases the coefficients may only represent a specific region and could be more appropriate for a traditional, i.e. API model, unitgraph. In addition to using a synthetic method, in some cases it is adequate to subjectively estimate the initial unit hydrograph to use with the Sacramento model based merely on typical time to peak information for major events, though this requires a certain amount of experience.

This author is not an expert on synthetic methods for deriving a unit hydrograph. Thus this manual will not include a discussion of the pros and cons of each procedure. The only warning offered when using a synthetic method is for slower responding watersheds where the storm hydrograph doesn't typically peak until days, rather than hours, after the rainfall or snowmelt occurs. For fast responding watersheds, most of the synthetic methods will give similar results, but for slower responding watersheds, none of the methods may produce the proper time delay. Figure 7-6-8 shows initial unit hydrographs generated from several methods for the Coosawattee River near Ellijay, Georgia which peaks quite quickly. Three

Figure 7-6-8. Unit hydrographs derived with different methods for Ellijay, GA.

Figure 7-6-9. Unit hydrographs derived with different methods for Tilton, GA.

synthetic unit hydrographs are compared to one derived from actual hydrograph data. For this watershed that peaks in 12 hours, all the unitgraphs are quite similar. Figure 7-6-9 is for the Conasauga River at Tilton, Georgia. For this watershed that takes a couple of days to peak, the synthetic methods all produce unit hydrographs that peak much quicker than the one derived from actual storm data. The unitgraph generated by the SCS method is more delayed than the other synthetic ones, however, the person who generated the synthetic unitgraphs was warned prior to running the SCS method that the time delay was quite a bit longer than the other synthetic methods were showing and thus the coefficients were changed based on this information to produce a longer delay. For watersheds that don't have a unit hydrograph with the typical shape associated with most drainage areas, generally due to the geometry of the drainage area, the time-area methods should have a better chance of having the proper shape than other synthetic methods, though there still may be problems with the timing for slow responding watersheds.

Other Considerations when Deriving Initial Unit Hydrographs

There are several other items that should be considered when deriving and using unit hydrographs. These include:

Watersheds with Multiple Zones - When a watershed is divided into several zones, typically either based on elevation or travel time, for rainfall-runoff computations, there are two basic sequences that can be followed when applying a unit hydrograph. First, the runoff from each zone can be weighted and the resulting mean watershed runoff can be applied to a single un it hydrograph for the drainage area. Second, the runoff from each zone can be applied to a separate unit hydrograph and then the results combined to produce the instantaneous flow hydrograph for the watershed. If separate unitgraphs are to be used for each zone, it is generally not possible to derive the response for each zone from a hydrograph analysis unless events can be found where all of the runoff comes from only one zone per event. Typically in this case one of two approaches are followed. One approach is to derive a total watershed unit hydrograph from storm data and then divide it into unitgraphs for each zone in such a way that the combined response is the same as the unit hydrograph derived for the total area taking into account that the runoff contribution from each zone may not have been the same. Another approach is to use a synthetic method to derive the unitgraph for each of the zones individually. For zones where no runoff reaches the designated river location for some period of time, i.e. there is some distance between the river location and the closest part of the zone, either zero ordinates can be inserted at the beginning of the unitgraph or the LAG/K operation can be used to lag the unitgraph by the required amount.

For watersheds that are divided into multiple zones based on travel time, separate unit hydrographs should be used for each zone or it defeats the purpose for subdividing the watershed. For watersheds with multiple elevation zones, it depends largely on the distribution of the elevation zones as to whether single or multiple unit hydrographs should be used. When the elevation zones are significantly related to distance from the river location, then separate unitgraphs are recommended for each zone. However, when the higher elevation zone has sort of a horseshoe pattern around the watershed divide (thus some portions of the upper zone are closer to the gage than a large part of the lower zone) then the use of a single unit hydrograph for the watershed is generally adequate. Also, in these cases it is typically very difficult to derive separate unitgraphs that can be verified as to their timing and shape.

<u>Time Interval of Ordinates</u> – Unit hydrographs are designated with a time interval that represents the time interval associated with the runoff being applied to the unitgraph. Thus, if 6 hour runoff data are being calculated and passed through a unit hydrograph to obtain discharge at a point on the river, a 6 hour unit hydrograph must be used. The time interval associated with the unit hydrograph has nothing to do with the ordinate spacing that is used to define the unitgraph. A unit hydrograph is a continuous curve that defines the instantaneous hydrograph produced by one unit of runoff over a specified time interval. The ordinates that are used to define that curve can be at whatever time interval is necessary to adequately define the shape of the curve. Thus, for example, if a 6 hour unit hydrograph for a watershed typically peaks in 15 hours, 3 hour ordinate spacing should be used to define the unitgraph so that the peak will occur in 15 hours and not in 12 or 18 hours as would be required if the ordinates were defined at 6 hour intervals.

<u>Variable Channel Response</u> – For some watersheds the shape and timing of the unit hydrograph is related to the flow level. This normally occurs when the channel width increases significantly as the flow goes over the bank and there is considerable roughness in the flood plain. This is the same physical situation that exists for channel reaches that require variable routing parameters at different flow levels. This situation is quite common in areas with only a

slight amount of channel slope, a fairly broad flood plain that contains a lot of vegetation, and flood levels that can be considerably higher than the flood plain elevation. Typically for such watersheds the channel response has much more attenuation when the stream first goes out onto the flood plain and then the attenuation decreases as the flow level increases and the effect of the flood plain roughness is diminished. This effect can be modeled by using a routing procedure that allows a variable amount of attenuation, such as a variable K in the LAG/K operation, as a function of the flow level immediately after the unit hydrograph is applied.

The unit hydrograph defined is for the flow level with the minimum amount of attenuation and then attenuation is added as needed at other flow levels with the routing model.