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**MARYLAND DEPARTMENT OF TRANSPORTATION  
STATE HIGHWAY ADMINISTRATION**

**RESEARCH REPORT**

***RESEARCH ON DIMENSIONLESS UNIT HYDROGRAPH AND  
TIME OF CONCENTRATION FOR MARYLAND WATERSHEDS***

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## Introduction

The goal of this study was to investigate two properties of unit hydrographs (UH) for Maryland watersheds: time of concentration,  $T_c$ , and Peak Rate Factor, PRF. The Natural Resources Conservation Service (NRCS) UH, as implemented in their WinTR-20 software, is widely used in Maryland. The PRF and  $T_c$  together define the shape and scale of the NRCS UH.

A hydrograph is a representative of watershed response, in terms of volumetric flow rate, to a certain precipitation event as a time function. They are normally used by engineers to assist in designing hydraulic structures (e.g., culverts, bridges, dams...). For design purposes, one of the most practical ways to estimate final design hydrograph is to convolve unit hydrographs of watersheds with associated precipitation events. (i.e., 20-year storm) (Horst & Gurriell, 2019). Unit hydrographs (UH) are crucial tools to estimate runoff hydrograph resulting from storm rainfall. The application of unit hydrograph is primarily on the runoff estimation on ungauged watersheds, in which they are known as synthetic unit hydrographs. Unit hydrograph models were developed by Clark (1945), Snyder (1938), and Mockus (1957) and they are applied in a variety of hydrological modelling (Sheridan et al., 2002).

A UH can be established through analysis of the precipitation-runoff events which can be found through historical data or through the analysis of various watershed characteristics applied in combination with a synthetic unit hydrograph model. Dooge (1959) discussed that the UH model to estimate stream flow is one of the most powerful tools in applied hydrology. Natural Resources Conversation Service unit hydrograph (a.k.a NRCS's synthetic unit hydrograph) method developed by Victor Mockus (1957) is among the most popular unit hydrograph models and is the basis of most engineering practice in the state of Maryland. This UH model makes use of a Peak Rate Factor to quantify the peak of the UH. Based on the NRCS formula, peak flow can be estimated as follows:

$$q_p = PRF \frac{AQ}{t_p} \quad (\text{Eq. 1})$$



where  $q_p$  = peak flow [cfs];  $PRF$  = peak rate factor;  $A$  = watershed area [ $\text{mi}^2$ ];  $t_p$  = time to peak [hr]. The PRF is both a unit conversion and a scaling factor between a dimensionless UH and the dimensional UH.

PRF is a representative of unit hydrograph shape (i.e., volume distribution). That is, it shows a degree of peakedness of the unit hydrograph. Typical PRF reproduced by Mockus (1957) is 484, which resemble the distribution of 3/8 of the volume of the streamflow runoff on the rising limb of the hydrograph and 5/8 of the streamflow volume on the recession side of the unit hydrograph. Alternatively, a PRF of 284 which is derived from Delmarva unit hydrograph (Welle et al. [1980]; Welle and Woodward [1989]) estimates a volume distribution of 22% under the unit hydrograph rising limb and 78% under the unit hydrograph receding side. PRF of 284 applies to the watersheds in coastal areas. Based on the handbook published in 1972, NRCS stated that “the value of the PRF vary from around 300 for roughly swampy and flat catchments to 600 for steep watersheds”, however, (NRCS 2007) based on the more recent research, PRF ranges from below 100 to above 600.

The accurate estimation of PRF is crucial for engineering design of hydraulic structures and current approaches do not seem to accurately estimate PRFs due to inconsistencies and erroneous process in the unit hydrograph modelling. This study aims to use fine-resolution sub-hourly precipitation data and associated sub-hourly runoff data for multiple events to model NRCS unit hydrograph and to estimate PRF and time of concentration for a series of watersheds. This study also investigates if there is any local/regional trend for estimated PRFs can be observed and if each watershed can be represented with a single PRF.

An additional objective of this study was to investigate watershed time of concentration ( $T_c$ ) and its dependence on watershed characteristics. This aspect of the research was intended to extend an in-depth study by W. Thomas and colleagues (2000) for the state of Maryland, which in turn built on work by Dillow (1998). We refer to that study as Thomas (2000).

## **Study Locations and Data**

Study locations were selected from USGS gaging stations. Since the decision was made to use WSR-88 Radar (NEXRAD) DPR product for the precipitation (discussed below), we were

limited to the time period for which those data are available. Our original intent was to select events between 1994 and 2017, however, the NEXRAD DPR product is only available starting in 2012. The annual maximum discharge time series for the gages were examined to identify events with peak flows greater than a 2-year return period (less than 50% annual exceedance probability). We selected event runoff hydrographs with a smooth, single-peak shape for consistency with the assumptions of the method. Additionally, watersheds were restricted in size to 100 mi<sup>2</sup> (259 km<sup>2</sup>) as larger catchments tend to be inconsistent with the assumptions of the unit hydrograph methodology.

The results discussed here are for a total of 54 gaging stations in the two provinces, 30 in Province 1 (Piedmont, Blue Ridge and Appalachian Plateau geographic regions) and 24 in Province 2 (Eastern and Western Coastal Plains). The stations are listed in Table 1; this table also identifies which stations were included in the Thomas (2000)  $T_c$  study (21 of 30 in Province 1, and 13 of 24 in Province 2). The study watershed locations are mapped in Figure 1. Further details on the study watersheds are provided later in this report.

The following section presents the steps followed to analyze the events. The steps are illustrated for a selected watershed and event. A complete catalog of results is provided as an Appendix to this report.

**Table 1. Watersheds Analyzed in this Study**

Province 1 (Piedmont, Blue Ridge, Appalachian Plateau)			Province 2 (Eastern and Western Coastal Plain)		
Station (USGS)	Number of Events	Included in Thomas (2000)	Station (USGS)	Number of Events	Included in Thomas (2000)
1580000	1	Y	1483200	1	Y
1581500	1	--	1484100	2	Y
1581700	3	Y	1485500	1	Y
1582000	1	Y	1486000	2	Y
1583100	2	Y	1486500	1	--
1583500	4	Y	1490000	1	--
1583570	1	--	1491500	2	--
1583580	1	--	1492500	3	--
1583600	1	Y	1493112	3	--
1584500	2	--	1493500	2	Y
1585200	1	Y	1581757	3	--
1586000	1	Y	1585090	1	--
1586210	3	Y	1585100	3	Y
1586610	2	Y	1585104	2	--
1589300	3	Y	1585230	1	--
1589440	7	Y	1589500	1	Y
1591000	6	Y	1594526	1	Y
1591400	3	Y	1649500	2	Y
1591700	3	Y	1651000	2	Y
1593500	1	Y	1653600	1	Y
1594000	2	Y	1658000	2	--
1596500	2	Y	1660920	2	Y
1599000	1	--	1661050	1	Y
1617800	3	Y	148471320	2	--
1637500	2	Y			
1639140	1	--			
1643500	4	Y			
1644371	2	--			
1644372	1	--			
1644375	1	--			

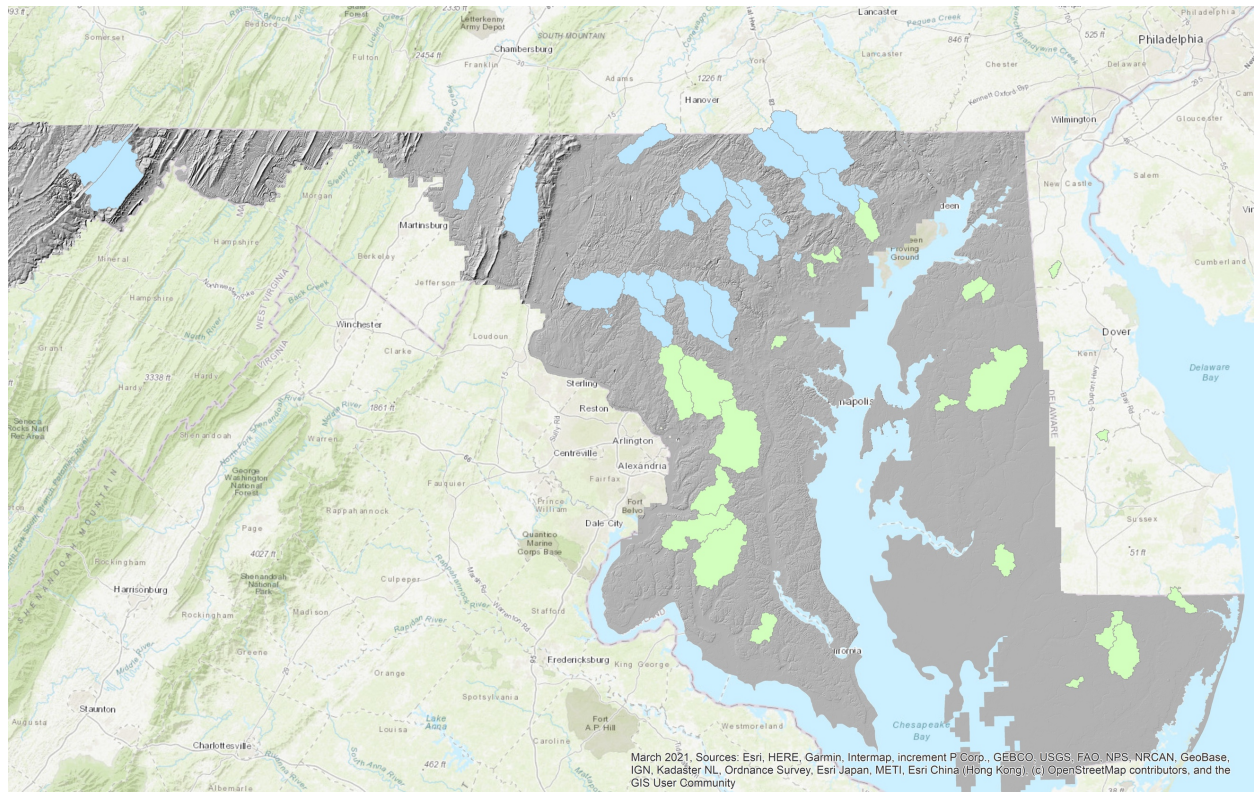


Figure 1. Watersheds selected for the study. Blue: Province 1 (Piedmont, Blue Ridge, and Appalachian Plateau); Green: Province 2 (Eastern and Western Coastal Plains). Map created in ESRI ArcMap. Some small or nested watersheds are hidden at this zoom level.

## **Methods**

### **Event Hydrograph Data**

For the selected discharge events, 15-minute stream gauge data were downloaded from U.S. Geologic Survey's (USGS) National Water Information System ([https://waterdata.usgs.gov/md/nwis/uv/?referred\\_module=sw](https://waterdata.usgs.gov/md/nwis/uv/?referred_module=sw)).

### **Event Hyetograph Data**

Corresponding precipitation events were required at sub-hourly rates. Very few sub-hourly precipitation gages are available in Maryland. This project introduces the application of the National Oceanic and Atmospheric Administration's (NOAA) Next Generation Weather Radar System (NEXRAD) products in developing unit hydrographs. Event hydrograph development followed these steps.

1. Archived Digital Precipitation Rate (DPR) data were downloaded from the National Centers for Environmental Information (NCEI) online data server. The DPR data are Level III, meaning that the information has been processed from the raw reflectivity signal to a gridded precipitation intensity. We selected the DPR data set because it provides precipitation intensity at sub-hourly time intervals, as frequently as 3 minutes in heavy events. The DPR data are available from 2012 to the present. Another Level III data set provided by NCEI, the Digital Precipitation Array (DPA) is available starting in May 1992; however, the DPA reports hourly accumulation at the same irregular times as the DPR, and at coarser resolution; time did not allow us to complete the computational steps to disaggregate the trailing-sum hourly accumulations to sub hourly intensities and depths as applied in our methods. The University Corporation for Atmospheric Research (UCAR) provides a Stage IV precipitation product at 4-km spatial resolution on regular 1-hour time intervals starting in 2002; however, this data set is not provided by the NCEI and we became aware of it very late in the course of this study. The applicability of that data set to this study and future work is discussed later in this report.

Several NEXRAD radars cover parts of Maryland. This study uses data from the WSR-88D radar at Sterling, Virginia (KLWX) because its range captures the entire state. Data are provided in a binary (non-text) format; NCEI recommends the use of their Weather and Climate Toolkit (WCT) application to view and process the data. The DPR data product is arranged on a radial

grid centered on the KLWX radar; the grid elements are 1 degree by 250 m (radial distance). The DPR radial grid is illustrated in Figure 2. We use the WCT to export a day's DPR values to comma-separated values (CSV) format text files, one for each reporting time during that day. NEXRAD records the DPR product as frequently as 3-minutes during intense rainfall; therefore, a 24-hour day could have up to 480 CSV files, each identified by date and time. We operate on

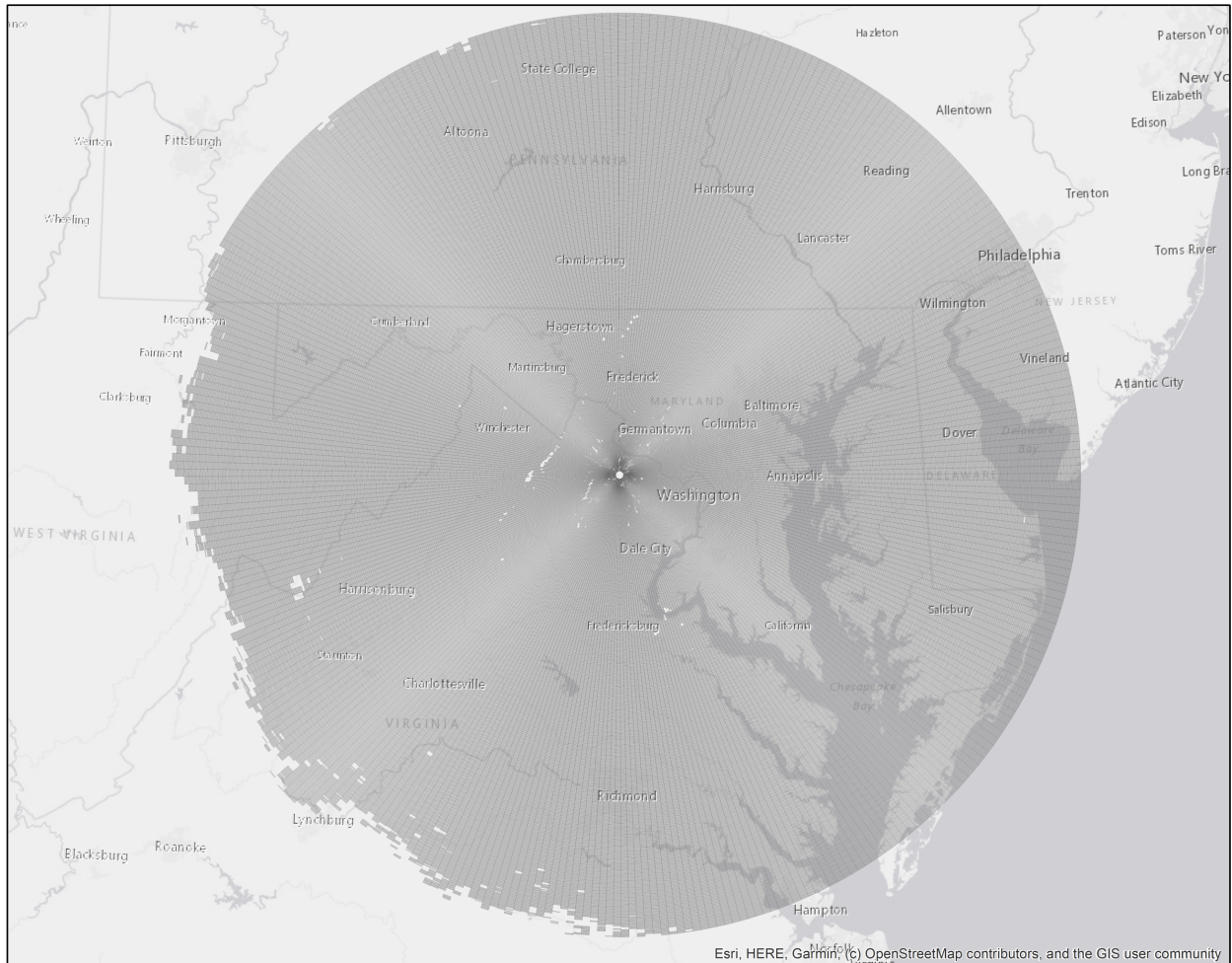


Figure 2. Example NEXRAD DPR image showing the radial grid centered on the Sterling, VA WSR-88D radar (KLWX). This image from Hurricane Sandy (October 2012) illustrates well the KLWX grid because precipitation is reported over nearly the entire sweep (the color scale normally seen in a radar image has been suppressed to emphasize the grid). DPR provides precipitation intensity for non-uniform cells 250 m in the radial direction and 1 degree in the angular direction. The grid consists of 360 angular increments and 920 radial increments, for a total of 331,200 irregularly sized grid cells. Individual cells are visible at the southwest border of the sweep image; the smooth edges elsewhere indicate complete coverage of detected precipitation to the maximum range (230 km).

these CSV files, using Unix text editing tools, to simplify them to a data set containing three columns: precipitation intensity value, angle, and radial distance.

2. For a given reporting time,  $t$ , average rainfall depth over a watershed is given by the integral of spatially-varying precipitation depth,  $p(\mathbf{x}, t)$ :

$$\bar{p}(t) = \frac{1}{A} \int p(\mathbf{x}, t) dA \quad (\text{Eq. 2})$$

where  $A$  is total area of the watershed. To perform this integral, each study watershed is subdivided into cells corresponding to the DPR's radial grid, using the polygon intersection tool in ArcGIS. We mapped the DPR polygons by using the WCT to export a single time sweep with nearly full coverage (Figure 2) in GIS shapefile format. An example of the watershed/DPR Grid intersection is shown in Figure 3(a). The area fraction of the watershed corresponding to each intersecting DPR grid cell is tabulated; an example is given in Figure 3(b). With each row of the DPR CSV file

corresponding to a cell in the grid, the average rainfall depth can be calculated as a weighted average,

$$\bar{p}(t) = \sum_{i=1}^n \frac{A_i}{A} p_i(t) \quad (\text{Eq. 3})$$

where  $n$  is the number of DPR radial grid cells that intersect with the watershed,  $A_i/A$  is the area fraction of the intersection, and  $p_i(t)$  is the DPR precipitation rate in that grid cell at that time. The DPR precipitation values and the area fractions are referenced to the DPR grid by (radial distance, angle) indices, 1 to 920

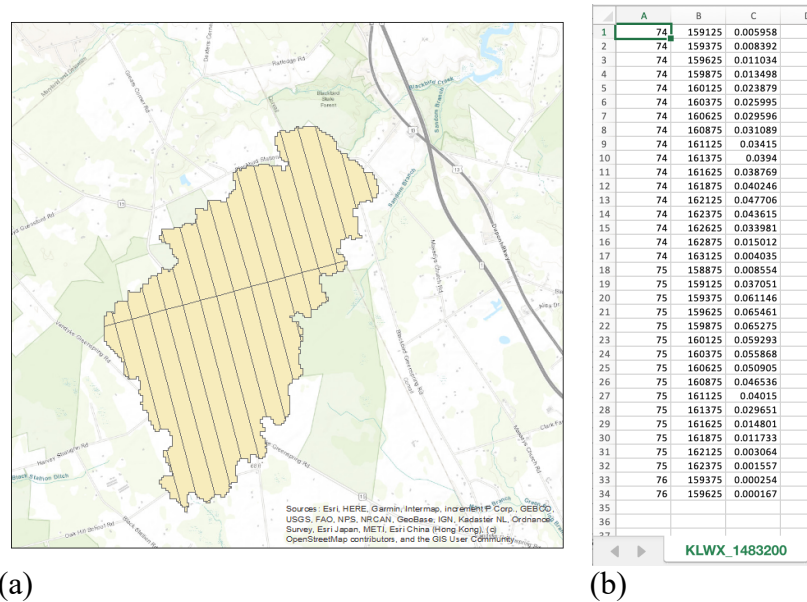


Figure 3. Example of polygon intersection of watershed with NEXRAD DPR angle-radius grid: USGS 1483200 Blackbird Creek at Blackbird, DE: (a) polygons in ESRI ArcMap; (b) CSV formatted file with angle and radial distance uniquely identifying each polygon.

for the radial distance and 1 to 360 for the angle. Watershed average precipitation rate can be efficiently calculated by elementwise multiplication (Hadamard product) of two matrices,

$$\bar{p}(t) = \alpha \odot \mathbf{P}(t) \quad (\text{Eq. 4})$$

where  $\mathbf{P}(t)$  is the (radial distance, angle) matrix of precipitation at time  $t$ , and  $\alpha$  is the (radial distance, angle) matrix of watershed area fractions. A Matlab script is used to calculate a time series of watershed average precipitation for each selected event.

3. The NEXRAD DPR data are finely resolved in space and time; however, they are subject to unquantified bias. We use an independent precipitation data set to adjust the watershed average time series. We selected the daily gridMET data, obtained from the online Climate Engine server (<http://climateengine.org/>). According to the gridMET webpage, “gridMET blends spatial attributes of gridded climate data from PRISM with desirable temporal attributes (and additional variables) from regional reanalysis (NLDAS-2) using climatically aided interpolation. The resulting product is a spatially and temporally complete, high-resolution (1/24th degree ~4-km) gridded dataset of surface meteorological variables.” Climate Engine allows us to download daily watershed average gridMET precipitation by uploading a shapefile outline of the watershed. Using a Matlab script, the fine-scale time series (at irregular time intervals) are cumulated and adjusted on a daily basis to match the daily watershed totals from gridMET. The corrected cumulated watershed average precipitation is disaggregated to a regular time interval of 0.1 hour (6 minutes). An example is shown in Figure 4.

The result of these three steps is an event hyetograph of watershed average precipitation at 6-minute (0.1-hour) intervals for the study watershed.



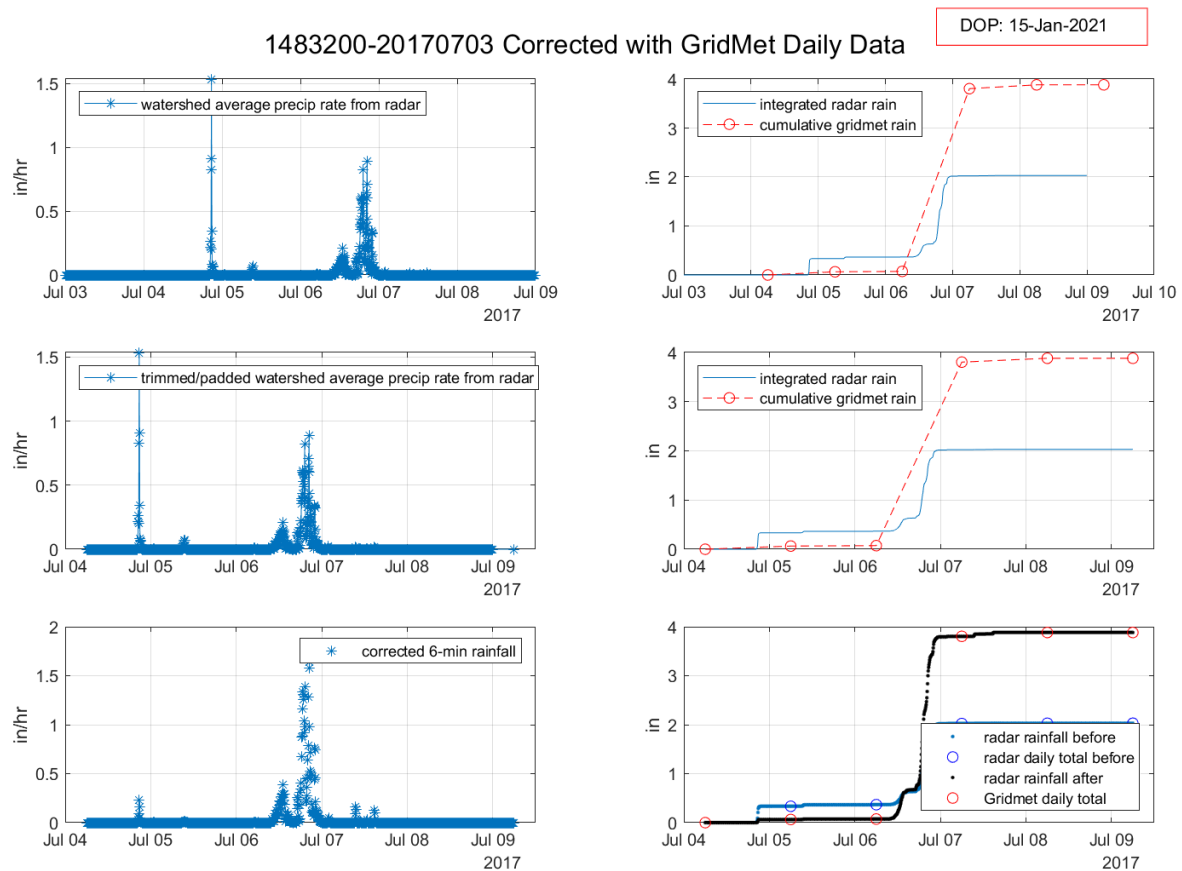


Figure 4. An example of adjusting watershed-average radar rainfall using gridmet watershed-average daily values. The original data, with radar data on a variable time step and gridmet data on a daily timestep (top row), are trimmed or extended as necessary to cover matching time periods (second row). The radar data are adjusted on a daily basis to match the gridmet, then disaggregated to a 6-minute time series (bottom row).

## Event Hydrograph and Hyetograph Processing

The Unit Hydrograph (UH) transforms precipitation excess into direct runoff. To derive a UH from a precipitation/runoff event, it is necessary to separate the event hyetograph into precipitation excess and losses (or abstracted precipitation) and to separate the runoff hydrograph into direct runoff (water that reached the stream gage by quick overland routes) and baseflow (water that reached the stream gage by infiltrating and moving more slowly to the gage, or water previously stored in the subsurface that flows to the gage during the event).

## *Baseflow Separation and Direct Runoff Estimation*

Several methods exist in the literature to separate baseflow from a hydrograph (e.g., constant-discharge, constant-slope, recursive filtering, concave, ...). Most graphical hydrograph separation methods require the analyst to identify an “inflection point” on the receding limb, which is assumed to indicate the end of direct runoff and the beginning of pure baseflow. This “inflection point” does not necessarily match the mathematical definition, and its identification is often subjective. We hoped to eliminate some of this subjectivity by applying an algorithm to automate the identification of baseflow recession. Pure baseflow is assumed to follow an exponential decay curve. The algorithm traces the recession curve and identifies the time after which the hydrograph best fits an exponential decay equation. That time is tagged as end of direct runoff / beginning of pure baseflow. In a modification of the concave method, baseflow is assumed to rise linearly from the beginning of the event until the end of the precipitation. At that time, the linear rise intersects the extended exponential recession curve and baseflow is defined for the entire event. In some cases, it is necessary to continue pre-event baseflow recession in a downward-sloping line for a short time before drawing the rising linear segment to connect to the recession curve, to avoid the assumed baseflow-rise line falling above the total hydrograph curve. Like other graphical separation methods, this one approximates the complex, spatially and temporally variable processes occurring in a watershed.

Once the baseflow is successfully separated, the time series of direct runoff (DRO) is calculated by subtracting baseflow from the total event hydrograph. The event depth of DRO is computed by numerical integration of the resulting DRO hydrograph. Our MATLAB script takes as input the event hydrograph, watershed area, and the date/time of the end of the precipitation event as inputs, separates the baseflow and finally estimates the direct runoff (DRO) volume (normalized by watershed area) as an output.

Figure 5 represents the result of baseflow separation for event 2017/07/03, watershed 1483200.

*Determination of Rainfall Excess*

Under the assumptions of the method, the depth of excess precipitation (PEX) equals the depth of the direct runoff. We separated rainfall excess from the event hyetographs using the phi-index method (e.g., McCuen 2016) implemented in a Matlab script. Conceptually, the phi-index method imposes a constant potential loss rate throughout the event, where loss could consist of storage or infiltration, or both. Actual loss during an increment of time equals precipitation or phi, whichever is less. An iterative solution identifies the value of phi at which integrated event excess precipitation equals direct runoff. An example is shown in Figure 6. [We also investigated the NRCS excess precipitation method, but the requirement of watershed curve number (CN) in that procedure created complications].

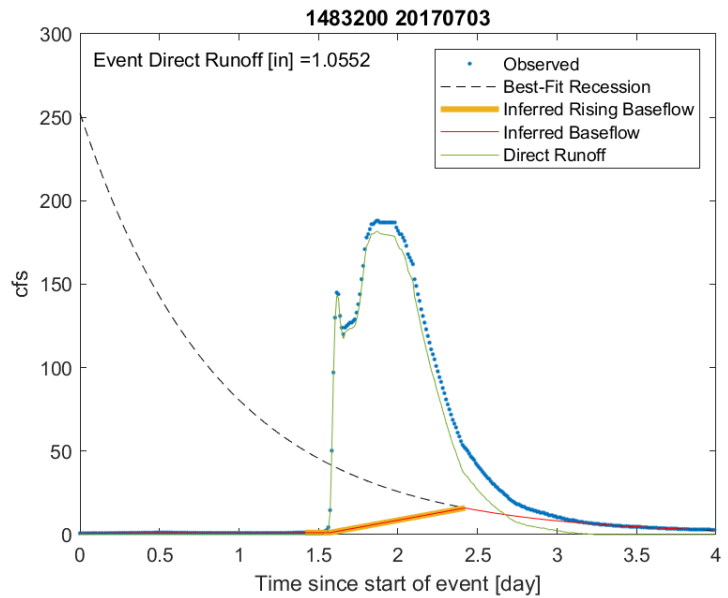


Figure 5. Baseflow separation example.

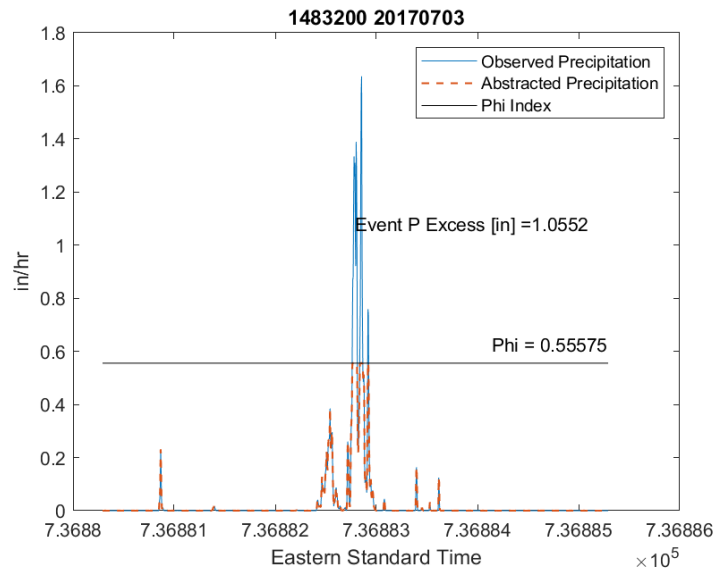


Figure 6. Example of Phi-Index precipitation separation.

## Unit Hydrograph Identification

The study imposes the gamma unit hydrograph (UH) to represent the transformation of precipitation excess to direct runoff in all the study watersheds. The UH approach assumes that the watershed's temporal runoff response to each increment of precipitation is identical in shape and proportional to precipitation in that increment of time. The event hydrograph is thus a convolution integral of the precipitation excess time series and the UH. Various methods are described in the literature to identify a UH from PEX and DRO time series. For this study, we implemented an optimization approach. The dimensionless unit hydrograph (DUH) is constrained to follow the gamma function described in NRCS (2007),

$$\frac{q}{q_p} = e^m \left( \frac{t}{t_p} \right)^m e^{-m \frac{t}{t_p}} \quad (\text{Eq. 5})$$

where  $q$  is discharge [cfs],  $q_p$  is peak discharge [cfs],  $t$  is time,  $t_p$  is time to peak, measured from beginning of hydrograph rise (assumed equal to beginning of precipitation excess), and  $m$  is the gamma function shape parameter. Eqn (5) can be rewritten to emphasize its dimensionless form,

$$q^* = e^m (t^*)^m e^{-mt^*} \quad (\text{Eq. 6})$$

Where  $q^*$  is dimensionless discharge ( $q/q_p$ ) and  $t^*$  is dimensionless time ( $t/t_p$ ). The function takes a maximum,  $q^* = 1$ , at  $t^* = 1$ . It equals zero at  $t^* = 0$  and is asymptotic to 0 as  $t^*$  becomes very large. Eqn. (6), the DUH, does not integrate to 1; the dimensional watershed unit hydrograph (UH) must express dimensional discharge as a function of dimensional time and must integrate to 1; these steps are discussed below.

For a given event, with  $DRO(t)$  and  $PEX(t)$  provided, the task is to find the gamma UH that best transfers  $PEX(t)$  to  $DRO(t)$ . There are two free parameters: unit hydrograph  $t_p$  and gamma shape parameter  $m$ .

The best-fit UH is determined by a quantitative objective function. We applied two different objective functions: (1) The sum of squared differences (SSE) between the observed hydrograph

and the convolved hydrograph, and (2) the match between predicted and observed peak discharge – magnitude and timing. Instead of using an optimization algorithm that systematically searches the mathematical  $(m, t_p)$  space to optimize the objective functions, our script explores the entire parameter space and calculates the objective functions for all possible parameter pairs. This way, we can observe how the fit between predicted (convolved) and observed DRO changes with the parameter pairs. We chose to use the gamma parameter  $m$  rather than the peak rate factor (PRF) at this step because  $m$  is dimensionless and more mathematically fundamental. The  $m$  parameter can easily be converted to its equivalent PRF (which is tied to the US Customary Unit System).

### *Estimation of the Unit Hydrograph*

For each event, a range of candidate  $m$  and a range of  $t_p$  are provided to the script, together with numerical increments to define the test values. For each possible  $(t_p, m,)$  pair, the DUH is calculated (Eqn. 6) using the candidate  $m$  and integrated numerically. The candidate dimensional unit hydrograph (UH) is obtained as follows: Each ordinate of the DUH is divided by the integral to ensure that the area under the dimensional unit hydrograph equals 1 (1 inch of direct runoff resulting from 1 inch of precipitation excess). The abscissae are divided by the candidate  $t_p$ , and the ordinates scaled to maintain area 1. The PEX hietograph is convolved with the candidate UH and the three objective functions are calculated: sum of squared errors (SSE), difference in peak discharge and difference in time to peak. After this process has been repeated for all candidate  $(t_p, m,)$  pairs, two best-fit  $(t_p, m,)$  pairs are identified: The one resulting in the minimum SSE, and the one at which the  $Q_{peak}$  error = 0 and  $T_{peak}$  error = 0 contours intersect. An example is shown in Figure 7. The solid-line contours show equal

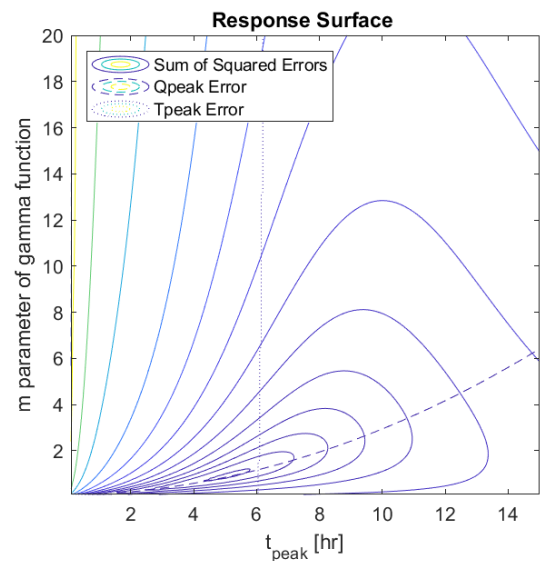


Figure 7. Response surface showing contours of three objective functions (measures of goodness of fit between predicted and observed hydrograph): overall sum of squared errors (solid contours), difference in magnitude of  $Q_{peak}$  (single dashed contour at  $Q_{peak}Error = 0$ ), and difference in time to peak (single light dotted contour at  $T_{peak} error = 0$ ).

values of SSE. The dashed line indicates the  $(t_p, m,)$  pairs where the peak discharge difference is zero ( $Q_{peak, predicted} = Q_{peak, observed}$ ). The light dotted line indicates the  $(t_p, m,)$  pairs where the time to peak difference is zero ( $t_{peak, predicted} = t_{peak, observed}$ ). In this case, the minimum SSE occurs at  $(t_p, m,) \cong (5 \text{ hr}, 1)$ . The predicted hydrograph peak matches the observed peak – both in magnitude and in timing – at  $(t_p, m,) \cong (6 \text{ hr}, 1.2)$ . The corresponding convolved hydrographs are shown in Figure 8.

The dimensionless and dimensional hydrographs corresponding to Figures 7 and 8 are shown in Figure 9.

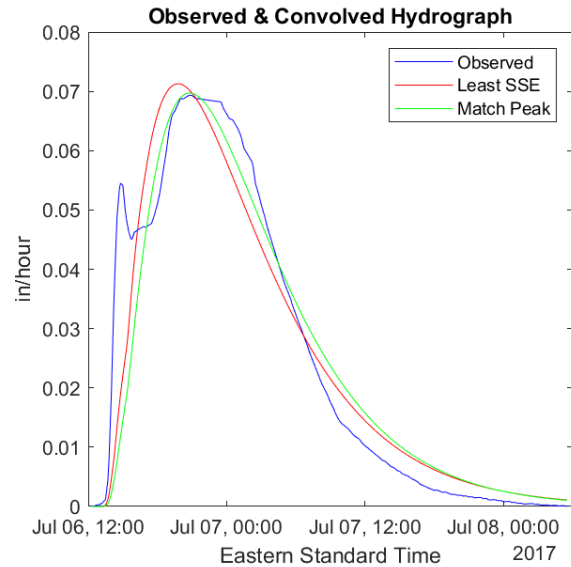


Figure 8. Hydrographs resulting from convolution of selected candidate unit hydrographs by two different goodness-of-fit measures (objective functions): overall Sum of Squared Errors (“Least SSE”) and best match to timing and magnitude of peak discharge (“Match Peak”).

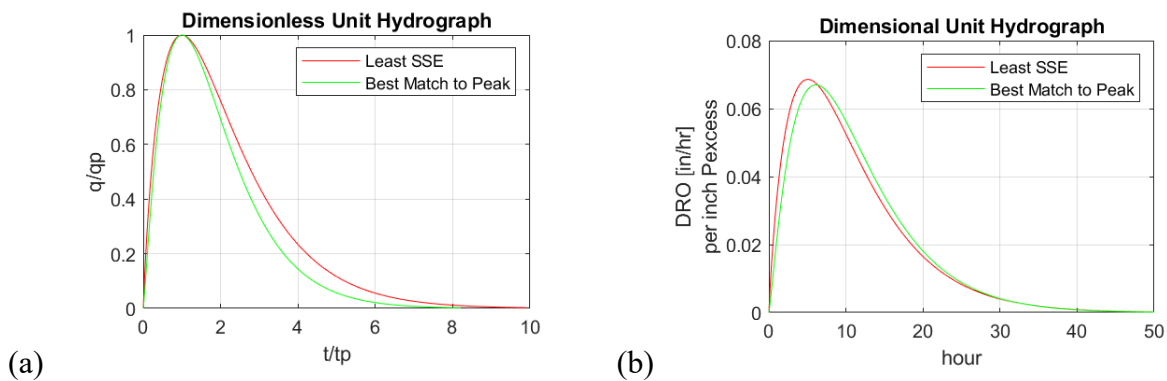


Figure 9. Dimensionless Unit Hydrograph (DUH) (a) and Dimensional Unit Hydrograph (UH) (b) corresponding to the optimal  $(m, t_p)$  selected by two different objective functions, as shown in Fig. 7. The DUH shapes (a) reflect only the difference in the gamma parameter  $m$ , and do not integrate to 1. The UH shapes (b) reflect different  $t_p$  as well. Both UH curves integrate to 1 inch of direct runoff.

The PRF is widely used in practice and is one of the target variables in this study. Therefore, we calculate and report PRF for each watershed event analyzed. value of the gamma  $m$  parameter

generates a unique dimensionless unit hydrograph and accordingly a unique PRF based on the following equation:

$$PRF = \frac{645.33}{\int q^* dt^*} \quad (\text{Eq. 7})$$

in which  $PRF$  is the peak rate factor. The integral in the denominator is dimensionless. Both the  $PRF$  and the constant 645.33 have units  $\text{cfs}/\text{mi}^2 / (\text{in}/\text{hr})$  (NRCS, 2010). Our Matlab script integrates the DUH numerically and reports the PRF.

### Determining Time of Concentration from Event Data

In this study, time of concentration [hr] was first estimated from the hydrograph and hyetograph of each event as the elapsed time between end of PEX and end of DRO. This measure is automatically extracted from the analyzed data after the hydrograph and hyetograph separation steps. Several decades of hydrologic practice have introduced numerous definitions of  $T_c$ . Conceptually, it is assumed to represent the time required for the entire watershed to contribute to runoff at the outlet. The end of direct runoff (sometimes called an “inflection point”) may or may not be appropriate to indicate this response time; if precipitation is assumed uniform over the watershed, it may be reasonable to assume that the final contribution to direct runoff is water arriving from the hydraulically most remote point in the watershed. By applying this automated calculation, we hoped to eliminate some subjectivity in determining  $T_c$ . It should be noted that – although automated and arguably objective – this measure is subject to numerous other assumptions and subjective decisions in the process of separating hydrograph and hyetograph. The calculation of  $T_c$  by this method for the example watershed event is illustrated in Figure 10.

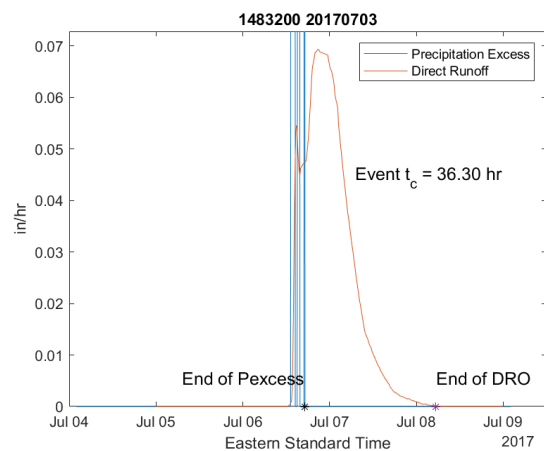


Figure 10. Example of automated determination of event Time of Concentration from Precipitation Excess hyetograph and Direct Runoff hydrograph.

A more conceptually rigorous approach is to determine the time from end of PEX to the inflection point on the receding limb of the event hydrograph. The inflection point is defined as the point at which the hydrograph changes from concave downward to concave upward; it represents a minimum value of the first derivative  $dQ/dt$ , that is, a zero of the second derivative,  $d^2Q/dt^2$ . Observations and physical reasoning indicate that this change in concavity represents the time at which water is draining from storage in the watershed, and therefore the time when the entire watershed has responded to the rainfall input (one definition of  $T_c$ ). We again tried to automate this identification procedure using a Matlab script. The script numerically differentiates the total discharge and the DRO hydrographs and identifies the minimum value of the first derivative on the recession limb. The point of minimum  $dQ/dt$  on the recession is identified; the minimum  $dQ/dt$  corresponds to a change in sign of the second derivative, and a change from concave downward to concave upward. This point is tagged as the inflection point; if several subsequent points in time share the

minimum derivative value, the times and discharges are averaged. The time at which precipitation excess (PEX) ends is recorded from prior analysis steps.  $T_c$  is calculated as the difference between the two times,  $T(\text{recession inflection}) - T(\text{PEX end})$ . The identification is performed for both the total discharge hydrograph and the direct runoff hydrograph. An example of this procedure is shown in Figure 11.

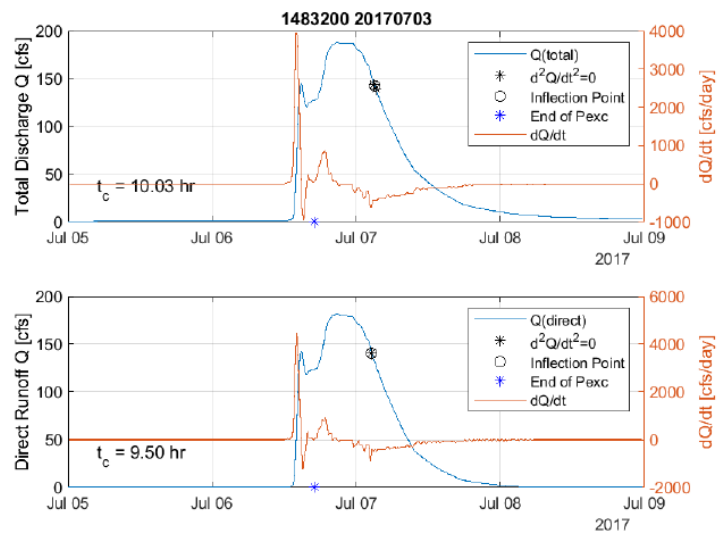


Figure 11. Identification of Time of Concentration using the event hydrograph recession inflection point. The hydrograph (blue) is numerically differentiated (red curve is first derivative  $dQ/dt$ ).

Through discussions with an expert colleague (W. Thomas, personal communication), we concluded that this method gives a  $T_c$  estimate that is more consistent with hydrologic practice than the end of PEX to end of DRO method described above. For a number of events, however, the end of PEX occurred after the inflection point on the hydrograph recession, leading to



negative  $T_c$ . It is not clear whether this irrational result stems from inaccurate precipitation time series or incorrect precipitation excess separation, or calls into question the inflection point approach to determining  $T_c$ . These negative  $T_c$ 's occurred in multiple watersheds for some of the heavy, long-lasting precipitation events in the data set. Ultimately, we employed a different estimation method to establish  $T_c$  for the study watersheds and events. The next section describes that method and demonstrates that it can substitute well for the event hydrograph inflection point method.

### Determining Time of Concentration from Unit Hydrograph

The mathematics of the NRCS curvilinear hydrograph assume that  $t_c$  is the time from the end of the unit precipitation excess to the mathematical inflection point on the receding limb of the hydrograph (NRCS 2010). Using the gamma unit hydrograph, the inflection point can be mathematically determined by taking the second derivative with respect to time, and setting it equal to 0,

$$t_{infl} = \left( \sqrt{\frac{1}{m} + 1} \right) t_p - 0.1 \quad (\text{Eq. 8})$$

where  $t_{infl}$  [hr] denotes the time of the inflection point on the dimensional unit hydrograph, measured from the end of precipitation excess (0.1 hr in this analysis). This time is calculated from each unit hydrograph and reported in a summary figure (example in Fig. 12). We denote this time as  $t_{infl}$ , time to inflection point, rather than  $t_c$ , to emphasize the different methods used in determining the variables.

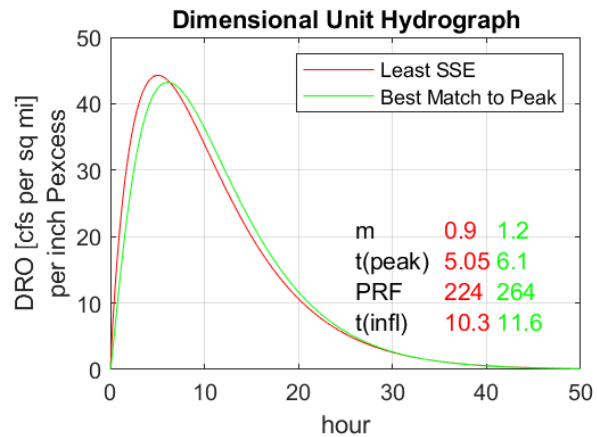


Figure 12. Example final results of unit hydrograph identification, giving values for two candidate UH's: gamma m, time to peak, Peak Rate Factor, and time from end of unit precipitation excess to recession inflection point.

## Results

The procedures described above were applied to all watersheds and events, for a total of 100 events, listed by watershed/station in Table 2. The graphical results for each event are included in the Appendix. As mentioned in the descriptions of the different steps, manual adjustments to the automated procedures were sometimes necessary to obtain rational results.

**Table 2. Stations and Number of Events Analyzed**

Station	Number of Events	Station	Number of Events	Station	Number of Events	Station	Number of Events
1483200	1	1582000	1	1586610	2	1639140	1
1484100	2	1583100	2	1589300	3	1643500	4
1485500	1	1583500	4	1589440	7	1644371	2
1486000	2	1583570	1	1589500	1	1644372	1
1486500	1	1583580	1	1591000	6	1644375	1
1490000	1	1583600	1	1591400	3	1649500	2
1491500	2	1584500	1	1591700	3	1651000	1
1492500	3	1585090	1	1593500	1	1653600	1
1493112	3	1585100	2	1594000	2	1658000	2
1493500	2	1585104	2	1594526	1	1660920	2
1580000	1	1585200	1	1596500	1	1661050	1
1581500	1	1585230	1	1599000	1	148471320	2
1581700	2	1586000	1	1617800	2		
1581757	1	1586210	3	1637500	2		
Total Number of Events							100
Total Number of Stations							54
Average Number of Events per Station							1.85
Number of Stations with 1 Event							27

## Analysis

The previous section described the identification of two different best-fit unit hydrographs for each event. In the remaining analysis, we use only the Least SSE solution. We judged that minimizing the sum of squared errors provides the best overall goodness-of-fit measure. (We have included the “Best Match to Peak” analysis in our catalog of results in the Appendix.)

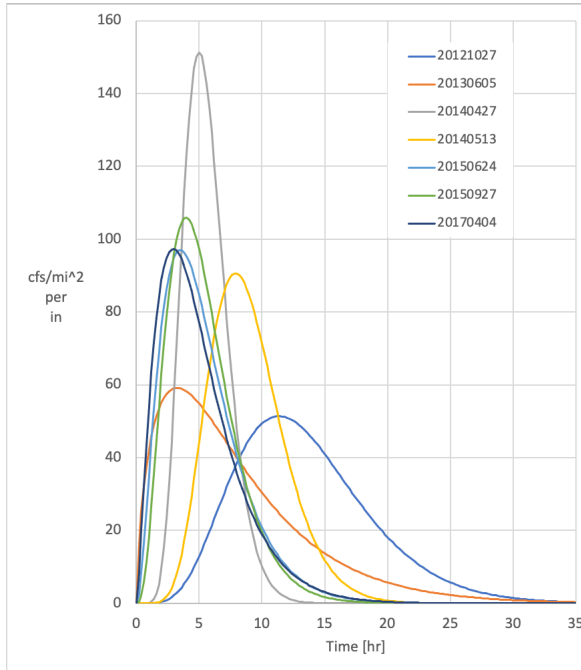


Figure 13. Unit hydrographs (0.1-hr PEXC) for Station 1589440 (Jones Falls at Sorrento, MD).

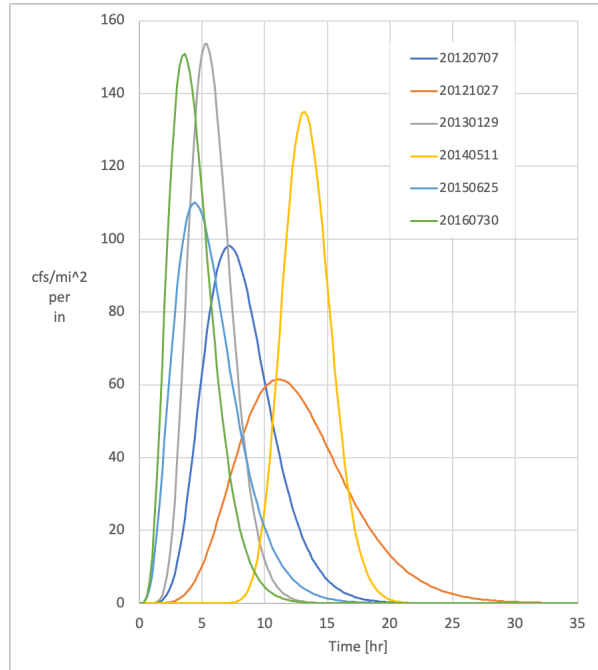


Figure 14. Unit hydrographs (0.1-hr PEXC) for Station 1591000 (Patuxent River near Unity, MD)

Watersheds where multiple events were available for analysis do not show consistency in the gamma  $m$ , the  $t_p$ , or the PRF. For example, the UHs identified from 7 events at Station 1589440 (Jones Falls at Sorrento, MD) are shown in Figure 13. Three events have similar UH; however, the remaining four differ noticeably in their shape (gamma  $m$ ) and time to peak. The UHs identified from 6 events at Station 1591000 (Patuxent River near Unity, MD) are shown in Figure 14. Similarities can be observed between pairs of UH; however, the results show a range of variation in the gamma  $m$  parameter and time to peak similar to Station 1589440.

Additionally, Figures 13 and 14 illustrate an apparent irrational result in the UH identification. For both stations, the UH for an event in May 2014 (20140513 and 20140511) begins to rise several hours after the precipitation excess begins. We consider this irrational because, by definition, the UH represents streamflow generated by precipitation excess after the delay due to initial abstraction and ongoing losses are removed from the precipitation time series. Under the assumption of spatially uniform unit PEXC over the watershed, the UH should begin to rise immediately when the PEXC begins.

All the analyzed events and the parameters of the Least SSE unit hydrographs are listed in Table 3. Events in which the UH is noticeably delayed are identified with a “†” symbol in Table 3. Many – but not all – of the events so identified have gamma  $m$  parameters greater than 12. Additionally, events for which the PEX convolved with the identified UH did not fit the observed hydrograph well (visual inspection) are marked with “\*” in Table 3. All graphical results are included in the Appendix.

**Table 3. Results of Unit Hydrograph and Time of Concentration Identification**

Station	Prov	Area [mi <sup>2</sup> ]	Event Date YYYY MM DD	Qpeak [cfs]	Return Period of Qpeak, T [yr]	Direct Runoff [in]	UH m [ ]	UH t_peak [hr]	UH t_infl [hr]	T_c from event data PEX to end DRO	Tc by Event Inflection Point		Note
											Total Q	DRO	
1483200	1	4.06	20170703	188	2<T<5	1.06	0.9	5.05	10.3	36.3	10.03	9.5	
1484100	2	3.31	20121026	136	25<T<50	1.2	7.7	15.35	20.8	37.7	15.88	17.8	
1484100	2	3.31	20150122	54.9	2<T<5	0.33	3.3	9.8	15.1	27.4	15.5	15.8	
1485500	2	45.47	20121027	1300	5<T<10	0.72	5.3	40.25	57.6	117.1	58.65	58.9	
1486000	2	3.98	20121027	288	5<T<10	1.13	4.2	12	17.8	51.2	9.95	15.7	
1486000	2	3.98	20161007	256	5<T<10	0.68	3.1	9.6	15	28.6	6.28	6.2	
1486500	2	11.18	20170810	1250	na()	3.68	1.5	17.95	32.5	69.5	36.5	47.3	
1490000	2	16.96	20161007	237	2<T<5	0.45	4.6	18.7	27.3	83.1	21.48	22.6	
1491500	2	87.67	20121026	4940	10<T<25	2.64	5.2	26.8	38.5	113.0	25.75	21.8	
1491500	2	87.67	20140427	1990	1.25<T<1.5	1.13	4.65	25.2	36.9	123.5	18.55	19.3	
1492500	2	8	20150116	267	2<T<5	0.57	3.1	9.1	14.2	28.6	10.31	28.5	
1492500	2	8	20160528	283	2<T<5	0.5	5.1	9.45	13.5	22.2	8.2	8.2	
1492500	2	8	20170805	843	10<T<25	1.78	0.7	3.9	8.5	41.4	4.45	4	
1493112	2	6.14	20140811	399	2<T<5	1.09	1.6	5.5	9.7	33.1	13.48	13.9	
1493112	2	6.14	20150626	1310	10<T<25	2.36	1.9	4	6.8	20.0	4.75	4.5	
1493112	2	6.14	20170727	361	2<T<5	0.79	3.85	7.4	11.1	20.7	5.55	5.6	
1493500	2	12.73	20170727	328	1.5<T<2	0.65	3.6	12.85	19.5	43.6	19.98	20.4	
1493500	2	12.73	20180209	667	2<T<5	1.7	15.1	23.7	29.7	67.7	5	5	*†
1580000	1	94.31	20130129	5020	2<T<5	0.67	2.3	4.25	7	26.7	2.8	2.8	
1581500	1	8.79	20170817	3680	10<T<25	1.81	2	1.45	2.4	7.7	1.75	2	
1581700	1	34.64	20150818	5680	5<T<10	0.5	3.8	1.4	2	17.2	1.3	1.6	
1581700	1	34.64	20170817	2800	2<T<5	0.28	1.8	1.35	2.3	13.5	1.68	1.6	
1581757	2	55.85	20140427	6150	na()	2.47	0.5	2.15	5.1	22.1	4.35	4.9	
1582000	1	53.7	20130129	4220	5<T<10	0.84	3.3	2.9	4.4	23.8	3.15	3.4	
1583100	1	12.45	20120825	1230	2<T<5	0.48	0.4	0.6	1.4	26.3	2.15	2.4	
1583100	1	12.45	20150928	1840	10<T<25	0.61	3.1	2	3	35.2	2.2	2.2	
1583500	1	60.31	20120824	6710	10<T<25	0.91	4.5	4.05	5.9	21.4	6.7	6.7	
1583500	1	60.31	20130129	6080	5<T<10	0.96	12.9	5.75	7.3	10.5	6	6.05	
1583500	1	60.31	20140427	3780	2<T<5	1.48	17.7	19	23.4	25.6	-12.6	-13.3	*
1583500	1	60.31	20150928	5060	5<T<10	0.63	5	4.7	6.7	29.2	6.75	6.8	
1583570	1	0.131	20170404	9.32	5	0.31	1	1.1	2.1	9.6	0.4	0.4	
1583580	1	1.49	20150928	283	5<T<10	0.22	1.7	1	1.7	7.0	0.47	0.5	*
1583600	1	20.88	20170402	1350	2<T<5	0.62	1.2	2.4	4.5	16.1	3.38	3.4	
1584500	1	36.04	20140427	5830	5<T<10	1.55	5	4.1	5.8	16.2	1.38	1.5	
1585090	2	2.58	20120813	1680	5<T<10	0.85	4.2	0.6	0.8	7.6	0.37	0.2	
1585100	2	7.56	20150624	4300	10<T<25	2.25	6.8	2.05	2.7	14.2	1.5	1.5	
1585100	2	7.56	20150712	1840	2<T<5	0.72	21.4	3.9	4.6	10.4	4.42	3.72	†
1585104	2	2.44	20120813	877	5<T<10	0.81	6.9	1.4	1.8	4.8	0.97	1	
1585104	2	2.44	20150624	1560	25<T<50	2.45	3.3	1.2	1.8	7.4	0.9	1.2	

Station	Prov	Area [mi <sup>2</sup> ]	Event Date YYYY MM DD	Qpeak [cfs]	Return Period of Qpeak, T [yr]	Direct Runoff [in]	UH m [ ]	UH t_peak [hr]	UH t_infl [hr]	T_c from event data PEX to end DRO	Tc by Event Inflection Point		Note
											Total Q	DRO	
1585200	1	2.31	20170817	1000	2<T<5	0.3	10.3	0.45	0.5	3.1	0.25	0.3	
1585230	2	3.5	20120628	2180	2<T<5	0.54	10.3	0.35	0.4	3.2	-1.93	-2	
1586000	1	55.48	20130129	5460	5<T<10	1.27	2.5	3.6	5.8	12.6	-7.05	-7	*
1586210	1	14.11	20130129	1520	5<T<10	1.43	1.9	2.45	4.1	4.4	-14	-14	*
1586210	1	14.11	20150928	1120	2<T<5	0.46	1.8	1.9	3.2	11.5	3.25	2.1	
1586210	1	14.11	20160729	1030	2<T<5	0.32	7.2	3.1	4.2	14.4	3.65	3.7	
1586610	1	28.01	20130129	3830	10<T<25	1.44	1.4	2.5	4.5	17.7	1.95	-2.8	*
1586610	1	28.01	20140514	1970	2<T<5	0.5	0.4	5	12.8	23.1	16.65	16.9	†
1589300	1	32.59	20121028	4060	5<T<10	2.61	5.9	11.95	16.8	9.2	-4	-3.7	
1589300	1	32.59	20150929	2920	2<T<5	0.83	5	6.05	8.7	21.0	8.6	8.9	
1589300	1	32.59	20160727	4700	5<T<10	1.43	1.9	3.4	5.8	18.2	7.8	8.1	
1589440	1	25.21	20121027	3510	5<T<10	2.86	5.3	11.35	16.2	44.4	-2.5	-2.2	
1589440	1	25.21	20130605	352	<1.25	0.23	0.7	3.25	7	29.0	-10	-10	
1589440	1	25.21	20140427	6400	10<T<25	3.32	8.8	5	6.6	28.1	-20.1	-19.8	
1589440	1	25.21	20140513	1210	2<T<5	0.48	7.9	7.9	10.6	26.7	11.25	11.5	
1589440	1	25.21	20150624	1730	2<T<5	0.63	1.9	3.5	5.9	30.0	7.35	7.6	
1589440	1	25.21	20150927	1010	1.5<T<2	0.33	2.8	3.95	6.2	18.0	7.6	7.6	
1589440	1	25.21	20170404	1170	2	0.49	1.4	2.95	5.3	24.6	5.65	5.7	
1589500	2	5.04	20121027	240	25<T<50	1.32	5.1	13.25	19	31.9	4.7	5	
1591000	1	34.95	20120707	1710	2<T<5	0.44	7.6	7.15	9.6	22.1	7.35	7.4	
1591000	1	34.95	20121027	3310	5	2.09	7.2	11.1	15.1	54.7	-3.38	-3.2	
1591000	1	34.95	20130129	4620	5<T<10	1.71	10.2	5.3	6.9	3.2	-6.95	-6.9	
1591000	1	34.95	20140511	2500	2<T<5	0.74	47.7	13.15	15	35.8	12.6	12.6	†
1591000	1	34.95	20150625	2640	2<T<5	0.62	3.7	4.4	6.6	17.9	7.5	7.5	
1591000	1	34.95	20160730	3740	5<T<10	0.72	4.5	3.55	5.1	28.0	5.85	6.1	
1591400	1	22.86	20130129	2330	5<T<10	1.42	4.2	3.5	5.1	10.4	-8.3	-8	
1591400	1	22.86	20150624	2080	5<T<10	0.83	2.5	3.5	5.6	18.1	7.15	7.4	
1591400	1	22.86	20160729	2390	5<T<10	0.69	3.1	2.85	4.4	22.3	4.6	4.6	
1591700	1	27.31	20121028	2180	2<T<5	1.75	6.6	9.85	13.6	13.2	-7.8	-12	*
1591700	1	27.31	20150626	2120	2<T<5	0.85	2.8	5.2	8.2	24.4	9.9	9.9	
1591700	1	27.31	20160729	2250	2<T<5	0.59	11.8	6.6	8.4	21.5	9.05	9.1	
1593500	1	38.1	20160729	7230	25<T<50	1.83	6.7	7.15	9.8	20.2	7.5	7.8	
1594000	1	98.25	20121027	10600	10<T<25	2.76	9.8	11.85	15.5	50.1	-1.35	-1.3	
1594000	1	98.25	20150624	5920	2<T<5	0.85	3	6.25	9.8	39.4	11.5	11.5	
1594526	2	89.38	20121027	4100	2<T<5	1.91	3.4	18.95	29.1	84.0	11.1	9.6	
1596500	1	48.53	20140511	2260	2<T<5	0.77	5.4	12.6	17.9	47.8	6.3	6.3	
1599000	1	72.74	20121027	2680	2<T<5	0.86	0.1	1	4.1	112.7	1.05	1.1	
1617800	1	18.34	20121027	121	2<T<5	0.15	2.4	11.75	19.2	43.6	11.9	12.2	
1617800	1	18.34	20180816	136	2<T<5	0.11	1.3	6.75	12.6	71.7	5.92	6.1	
1637500	1	67.33	20121027	8330	10<T<25	2.95	8.3	10.8	14.4	34.9	-3.48	-2.8	
1637500	1	67.33	20140511	6750	10<T<25	1.2	33.3	15.25	17.8	25.7	12.55	7.1	†

Station	Prov	Area [mi <sup>2</sup> ]	Event Date YYYY MM DD	Qpeak [cfs]	Return Period of Qpeak, T [yr]	Direct Runoff [in]	UH m [ ]	UH t_peak [hr]	UH t_infl [hr]	T_c from event data PEX to end DRO	Tc by Event Inflection Point		Note
											Total Q	DRO	
1639140	1	31.37	20121027	6150	25<T<50	3.39	4.2	12.95	19.2	7.2	1.75	-4.2	
1643500	1	62.94	20130129	5750	5<T<10	1.49	4	4.95	7.3	13.5	-7.4	-7.4	*
1643500	1	62.94	20140511	5950	5<T<10	1.04	35	11.9	13.8	26.8	11.8	11.8	†
1643500	1	62.94	20150928	2800	2<T<5	0.27	0.7	1.55	3.3	18.9	0.75	0.8	
1643500	1	62.94	20160727	3930	2<T<5	0.51	4.8	4.7	6.7	16.7	6.5	6.8	
1644371	1	0.42	20130608	252	5<T<10	0.8	3.7	0.45	0.6	2.1	-0.03	0	
1644371	1	0.42	20160729	396	10<T<25	1.32	1.8	0.325	0.5	3.7	0.35	0.3	
1644372	1	0.34	20160729	453	na()	1.33	3.6	0.575	0.8	2.1	0.12	0.1	
1644375	1	1.29	20130608	468	5<T<10	0.76	1.1	0.55	1	5.7	0.88	0.9	
1649500	2	73.2	20121027	4750	2<T<5	1.86	2	6.4	10.8	39.1	-12.1	-12.1	
1649500	2	73.2	20140609	7290	5<T<10	0.31	1	0.65	1.2	4.1	0.23	0.3	
1651000	2	49.33	20121027	5770	2<T<5	2.88	11	9.65	12.5	18.4	-11	-10.7	*
1653600	2	39.43	20121027	1630	2<T<5	1.35	9.8	17.4	22.9	35.4	4.7	2	†
1658000	2	55.57	20140427	1540	2<T<5	0.95	0.7	9.9	21.6	74.4	6.15	6.45	
1658000	2	55.57	20181009	5680	10<T<25	2.03	4.9	16.7	24.1	38.5	15.18	15.2	
1660920	2	81.61	20121027	2620	5<T<10	0.8	10.1	34.45	45.2	67.9	19.82	24.7	†
1660920	2	81.61	20140427	3370	10<T<25	1.85	5.9	26.4	37.2	95.9	24.25	26	
1661050	2	18.18	20170704	1410	2<T<5	0.98	5.1	9.95	14.3	41.7	9.8	7.8	*
148471320	2	6.38	20121026	1040	na()	4.75	0.5	2.55	6.1	35.0	-7.7	-19.4	
148471320	2	6.38	20170810	1290	na()	2.11	8.4	10.15	13.6	29.5	12.35	11.6	†

\* Convolved hydrograph is not a good fit with observed.

† Unit hydrograph does not rise at the beginning of Pexcess.

Event  $T_c$  determined as described above and tabulated in Table 3, is compared to observed average watershed  $T_c$  reported in Thomas (2000). It is important to note a major difference between the semi-automated method used here and the expert interpretation method applied in the previous study. This study measured the time elapsed from end of PEX to end of DRO where the end of DRO was determined using an exponential base-flow recession model. The Thomas (2000) study examined the hydrographs and identified the time from end of precipitation excess to the *first inflection point on the recession limb*. It is clear from Figure 15 that these two times are not the same. This study's event  $T_c$  is almost three times the previous expert-identified  $T_c$ .

If, instead, the Thomas (2000) expert-identified  $T_c$  is compared with the UH  $t_{infl}$  calculated in this study, the values are in much better agreement (Figure 16).

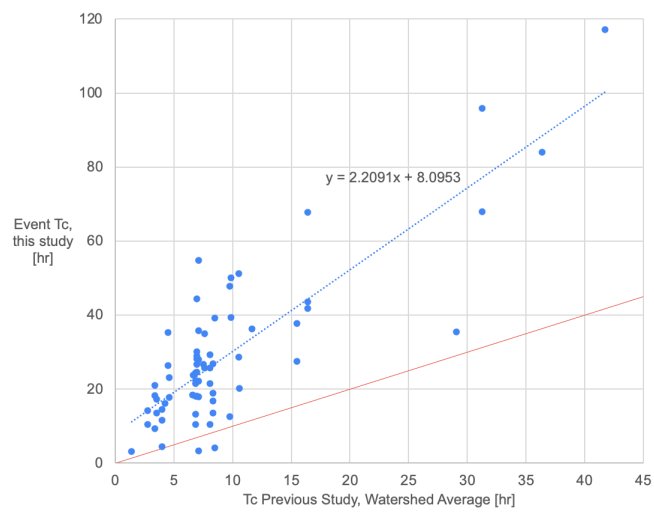


Figure 15. Event time of concentration identified in this study (time from end of precipitation excess to end of direct runoff) compared to watershed average  $T_c$  identified by expert inspection of hydrographs in the Thomas (2000) study (end of P excess to first inflection point on the recession). The dashed blue line is the calculated linear regression; the red line is the line of equality.

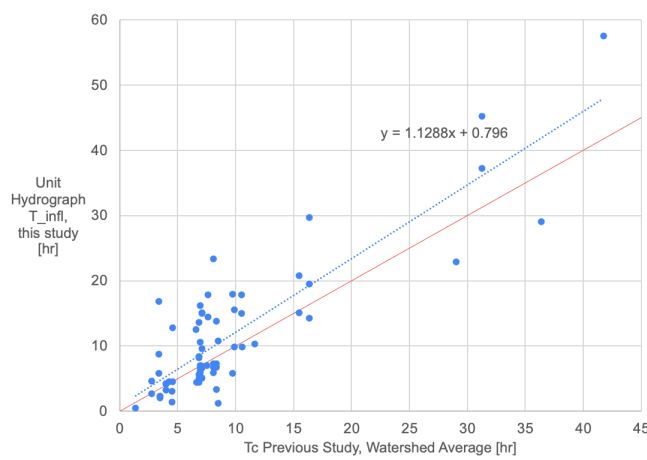


Figure 16. Time from end of Precipitation Excess to the mathematical inflection point on the gamma unit hydrograph ( $t_{infl}$ ), as calculated in this study, compared to watershed average time of concentration ( $T_c$ ) determined by expert inspection in the Thomas (2000) study. The dashed blue line is the calculated linear regression, and the red line is the line of equality.



The event  $T_c$  determined in this study by automatically determining the recession inflection point are compared to those determined in the Thomas (2000) study (Figure 17). This study's inflection-point values tend to underestimate, especially in the range of longer  $T_c$ .

Finally, the  $T_c$  estimated from the event hydrographs in this study is compared to  $t_{infl}$  calculated from the gamma equation of the UH (Figure 18). The values determined mathematically from the UH tend to be greater than those estimated graphically from the event hydrographs.

Given the large number of irrational results (negative  $T_c$ ) found using the graphical event analysis method and given the good agreement between  $t_{infl}$  and the Thomas (2000)  $T_c$  estimates, we decided to use the UH  $t_{infl}$  as the estimate of watershed/event Time of Concentration for the remaining analysis.

### Censoring Result Data

The events identified with \* or † in Table 3 were excluded from further analysis. The censored data set consists of 82 events at 47 stations. The remaining analysis consists of an effort to determine

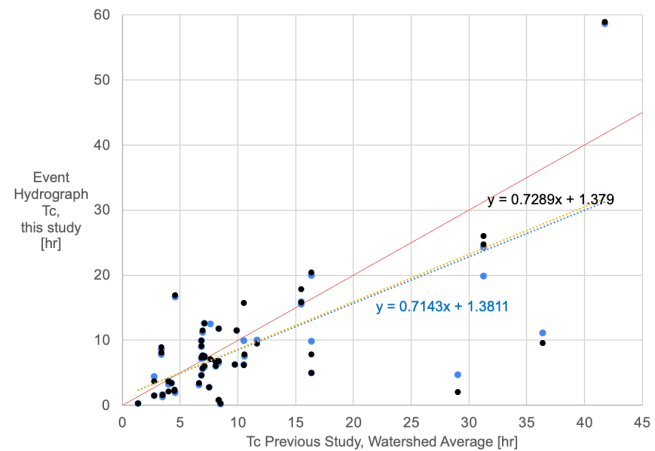


Figure 17.  $T_c$  estimated using the event hydrograph recession inflection point in this study compared to watershed average  $T_c$  estimated in Thomas (2000). Blue: estimated from total discharge hydrograph; Black: estimated from direct runoff hydrograph. Irrational negative  $T_c$  results are excluded. The red line is the line of equality.

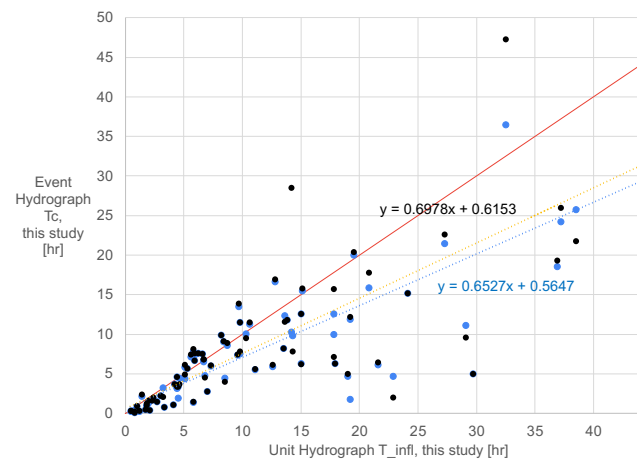


Figure 18.  $T_c$  estimated using the event hydrograph recession inflection point in this study compared to  $T_{infl}$  calculated from the equation of the gamma unit hydrograph. Blue: estimated from total discharge hydrograph; Black: estimated from direct runoff hydrograph. Irrational negative  $T_c$  results are excluded. The red line is the line of equality.

whether the parameters of the identified unit hydrographs ( $m$  and  $T_c$ ) can be related to or predicted by watershed properties.

### **Watershed Properties as Predictor Variables**

It is necessary to have a consistent set of watershed properties to test as predictors. Thomas (2000) found the following variables significant in predicting  $T_c$ :

- Channel length [mi]
- Channel slope [ft/mi]
- Forest cover [percentage of watershed]
- Impervious area [percentage of watershed]
- Storage in lakes and ponds [percentage of watershed]
- Geographical Province [binary variables, CP = 1 if in Coastal Plain, 0 otherwise; AP = 1 if in Appalachian Plateau, 0 otherwise]

The values used as input to stepwise regression in Thomas (2000) are provided in Table A6-4 of the Hydrology Panel Report (2020).

Of our censored data, 21 watersheds were included in the Thomas (2000) Study, and 26 were not. For a consistent data set that includes all our study watersheds, we consulted Appendix 1 of the Hydrology Panel Report (HPR-App1), which provides several dozen watershed properties. There are some inconsistencies between Table A6-4 and HPR-App1. The reason for the inconsistencies is that the values in Table A6-4 were determined by Dillow (1998) and the values in Appendix 1 were determined using GIS techniques after 2006. The Dillow (1998) watershed characteristics were retained in Table A6-4 to document the watershed characteristics used in the Thomas and others (2000) study (W. Thomas, personal communication).

Channel Length, which was identified as a significant predictor in the previous study, is not provided in HPR-App1; HPR-App1 reports a “Total Stream Length” variable, which is not the same. We chose to use Watershed Length, which is reported by HPR-App1 and calculated in GISHydroNXT’s Basin Statistics step, as the predictor variable instead. This variable is defined as “distance measured along the main channel from the watershed outlet to the basin divide (mi)”

(HPR). The values are strongly correlated with, but slightly greater than, the Channel Length variable used in Thomas (2000) (Figure 19). However, HPR-App1 does not provide values of the length variable for all the study watersheds. The watersheds with missing Watershed Length were analyzed using watershed analysis in GISHydroNXT. The basin statistics output files are included in the Appendix to this report.

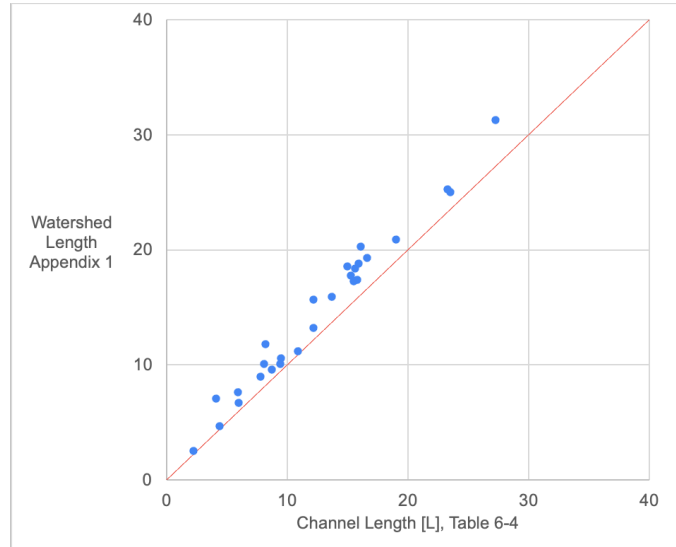


Figure 19. Channel Length from Maryland Hydrology Panel (2020) Table A6-4 and Watershed Length as reported in Maryland Hydrology Panel (2020) Appendix 1 for watersheds included in the Thomas (2000) study.

Four of our study watersheds are not included in HPR-App1: 1486500 (Beaverdam Creek Near Salisbury, Md), 1581757 (Otter Point Creek Near Edgewood, Md), 1639140 (Piney Creek Near Taneytown, Md.), and 1644372 (Little Seneca Creek Tributary at Brink, Md). The required input properties for these four were determined using watershed analysis in GISHydroNXT. The basin statistics output files are included in the Appendix.

Stepwise regression was performed using the Matlab tool/command “stepwiselm.” A first test was to run this tool on the Thomas (2000) data provided in HPR Table A6-4. Thomas (2000) used different software tools; the purpose of this test was to confirm that the Matlab tool performs similarly. All rows in HPR Table A6-4 with missing data were removed, leaving 77 observations. The result of this linear regression is:

$$Tc = 0.1654 SL^{-0.202} CL^{0.4678} (ST+1)^{0.1463} (101-FOR)^{-0.1541} (101-IA)^{0.838} 10^{0.191} AP 10^{0.36} CP$$

The Matlab stepwise regression identifies the same set of significant predictors as Thomas (2000). Table 4 compares the coefficients determined in this exercise to those reported by

Thomas (2000); the exponents deviate from the Thomas (2000) values by several percent; these differences can be attributed to internal computational procedures in the software packages.

**Table 4. Results of Stepwise Regression on Thomas (2000) Data to Confirm Consistency of Analysis: Coefficients**

	Constant	SL	CL	ST+1	101-FOR	101-IA	AP	CP
Thomas (2000)	0.1654	-0.202	0.4678	0.1463	-0.1541	0.838	0.191	0.36
Test regression	0.133	-0.187	0.475	0.154	-0.144	0.861	0.194	0.366
Fractional difference relative to Thomas (2000)	-0.196	-0.074	0.015	0.053	-0.066	0.027	0.016	0.017

Stepwise regression was performed on the data matrix presented in Table 5. The 12 columns DA through DRO are the predictor variables, and the last 3 columns M, TPEAK, and TINFL are the criterion or response variables. Multiple events on the same watershed were not averaged, because we hypothesized that unit hydrograph properties might reflect differences in event magnitude (DRO). Except for the Province indices CP, PM, BR, and AP, all variables were log transformed for the regression analysis. Forest and Impervious Area percent were transformed as  $\log_{10}(101 - \text{FOR})$  and  $\log_{10}(101 - \text{IA})$  and Storage was transformed as  $\log_{10}(\text{ST} + 1)$  as in Thomas (2000), to avoid the possibility of attempting to log transform a value of 0.

The correlation structure of the predictor and response variables is presented in Table 6, which follows Table 5 below.

In Table 5, the variables are defined as follows:

Date YYYYMMDD

Predictor Variables

- DA Drainage Area, [mi<sup>2</sup>]
- L Watershed length [mi]
- CS Channel Slope [ft/mi]
- LS Land Slope [ft/ft]
- FOR Percent (by area) forested
- IA Percent (by area) impervious
- ST Percent of area representing storage (lakes, ponds, wetlands)
- CP Index variable for Coastal Plain province
- PM Index variable for Piedmont province
- BR Index variable for Blue Ridge province
- AP Index variable for Appalachian Plateau province
- DRO Direct Runoff [in]

Response Variables

- m Gamma UH m parameter
- tpeak UH Time to peak of the UH
- tinfl UH Time from end of unit Precipitation to recession inflection point of the UH, used as estimate of Time of Concentration

**Table 5. Predictor and Response Variables Used in Stepwise Regression**

Station	Date	DA	L	CS	LS	FOR	IA	ST	CP	PM	BR	AP	DRO	m	tpeak UH	tinfl UH
1483200	2017 0703	4.06	4.01	13.5	0.01898	30	4.3	21.4	1	0	0	0	1.06	0.9	5.05	10.3
1484100	2012 1026	3.31	3.62	5.2	0.0073	19.8	2	25	1	0	0	0	1.2	7.7	15.35	20.8
1484100	2015 0122	3.31	3.62	5.2	0.0073	19.8	2	25	1	0	0	0	0.33	3.3	9.8	15.1
1485500	2012 1027	45.47	15.7	3.1	0.00841	72.8	2.3	0.3	1	0	0	0	0.72	5.3	40.25	57.6
1486000	2012 1027	3.98	7.1	6.4	0.00544	46.9	2.2	0	1	0	0	0	1.13	4.2	12	17.8
1486000	2016 1007	3.98	7.1	6.4	0.00544	46.9	2.2	0	1	0	0	0	0.68	3.1	9.6	15
1486500	2017 0810	11.18	6.23	6.354	0.01286	35.4	16.2	1.4	1	0	0	0	3.68	1.5	17.95	32.5
1490000	2016 1007	16.96	8.4	5.6	0.00757	43.2	0.9	0.5	1	0	0	0	0.45	4.6	18.7	27.3
1491500	2012 1026	87.67	18.7	3.3	0.01189	31	1.3	0.1	1	0	0	0	2.64	5.2	26.8	38.5
1491500	2014 0427	87.67	18.7	3.3	0.01189	31	1.3	0.1	1	0	0	0	1.13	4.65	25.2	36.9
1492500	2015 0116	8	7.4	9.9	0.01948	29.3	1.3	0	1	0	0	0	0.57	3.1	9.1	14.2

Station	Date	DA	L	CS	LS	FOR	IA	ST	CP	PM	BR	AP	DRO	m	tpeak UH	tinfl UH
1492500	2016 0528	8	7.4	9.9	0.01948	29.3	1.3	0	1	0	0	0	0.5	5.1	9.45	13.5
1492500	2017 0805	8	7.4	9.9	0.01948	29.3	1.3	0	1	0	0	0	1.78	0.7	3.9	8.5
1493112	2014 0811	6.14	5.11	14.6	0.01857	7.9	0.4	0.5	1	0	0	0	1.09	1.6	5.5	9.7
1493112	2015 0626	6.14	5.11	14.6	0.01857	7.9	0.4	0.5	1	0	0	0	2.36	1.9	4	6.8
1493112	2017 0727	6.14	5.11	14.6	0.01857	7.9	0.4	0.5	1	0	0	0	0.79	3.85	7.4	11.1
1493500	2017 0727	12.73	7.6	9.9	0.02445	7.2	1	0.5	1	0	0	0	0.65	3.6	12.85	19.5
1580000	2013 0129	94.31	31.3	17.9	0.103	25.8	3.9	0.1	0	1	0	0	0.67	2.3	4.25	7
1581500	2017 0817	8.79	7.1	45.1	0.048	14.8	33.4	0	0	1	0	0	1.81	2	1.45	2.4
1581700	2015 0818	34.64	17.4	30.4	0.07	25.9	13	0	0	1	0	0	0.5	3.8	1.4	2
1581700	2017 0817	34.64	17.4	30.4	0.07	25.9	13	0	0	1	0	0	0.28	1.8	1.35	2.3
1581757	2014 0427	55.85	25.87	27.27	0.08477	27	17.8	0.2	0	1	0	0	2.47	0.5	2.15	5.1
1582000	2013 0129	53.7	18.6	33.1	0.103	38.3	5.3	0.1	0	1	0	0	0.84	3.3	2.9	4.4
1583100	2012 0825	12.45	9	49.8	0.083	30.8	4.7	0	0	1	0	0	0.48	0.4	0.6	1.4
1583100	2015 0928	12.45	9	49.8	0.083	30.8	4.7	0	0	1	0	0	0.61	3.1	2	3
1583500	2012 0824	60.31	18.8	26	0.082	33.7	4.4	0.1	0	1	0	0	0.91	4.5	4.05	5.9
1583500	2013 0129	60.31	18.8	26	0.082	33.7	4.4	0.1	0	1	0	0	0.96	12.9	5.75	7.3
1583500	2015 0928	60.31	18.8	26	0.082	33.7	4.4	0.1	0	1	0	0	0.63	5	4.7	6.7
1583570	2017 0404	0.131	0.73	215.1	0.101	100	0	0	0	1	0	0	0.31	1	1.1	2.1
1583600	2017 0402	20.88	11.8	45.6	0.076	23.7	27.5	0.1	0	1	0	0	0.62	1.2	2.4	4.5
1584500	2014 0427	36.04	15.5	21.8	0.071	28.5	6.8	0.1	0	1	0	0	1.55	5	4.1	5.8
1585090	2012 0813	2.58	3.31	81.9	0.06888	9.3	47.2	0	0	1	0	0	0.85	4.2	0.6	0.8
1585100	2015 0624	7.56	6.7	54.4	0.061	14.3	42.6	0	0	1	0	0	2.25	6.8	2.05	2.7
1585104	2012 0813	2.44	3.39	72.1	0.054	28.6	22.5	0	0	1	0	0	0.81	6.9	1.4	1.8
1585104	2015 0624	2.44	3.39	72.1	0.054	28.6	22.5	0	0	1	0	0	2.45	3.3	1.2	1.8
1585200	2017 0817	2.31	2.5	63.1	0.059	2	43.2	0	0	1	0	0	0.3	10.3	0.45	0.5
1585230	2012 0628	3.5	3.8	82.1	0.045	1.8	45.4	0	0	1	0	0	0.54	10.3	0.35	0.4

Station	Date	DA	L	CS	LS	FOR	IA	ST	CP	PM	BR	AP	DRO	m	tpeak UH	tinfl UH
1586210	2015 0928	14.11	10.1	45	0.079	24.6	14.5	0.2	0	1	0	0	0.46	1.8	1.9	3.2
1586210	2016 0729	14.11	10.1	45	0.079	24.6	14.5	0.2	0	1	0	0	0.32	7.2	3.1	4.2
1589300	2012 1028	32.59	15.9	21.2	0.056	21.2	35.7	0.2	0	1	0	0	2.61	5.9	11.95	16.8
1589300	2015 0929	32.59	15.9	21.2	0.056	21.2	35.7	0.2	0	1	0	0	0.83	5	6.05	8.7
1589300	2016 0727	32.59	15.9	21.2	0.056	21.2	35.7	0.2	0	1	0	0	1.43	1.9	3.4	5.8
1589440	2012 1027	25.21	10.6	32.3	0.078	23.7	18.9	0	0	1	0	0	2.86	5.3	11.35	16.2
1589440	2013 0605	25.21	10.6	32.3	0.078	23.7	18.9	0	0	1	0	0	0.23	0.7	3.25	7
1589440	2014 0427	25.21	10.6	32.3	0.078	23.7	18.9	0	0	1	0	0	3.32	8.8	5	6.6
1589440	2014 0513	25.21	10.6	32.3	0.078	23.7	18.9	0	0	1	0	0	0.48	7.9	7.9	10.6
1589440	2015 0624	25.21	10.6	32.3	0.078	23.7	18.9	0	0	1	0	0	0.63	1.9	3.5	5.9
1589440	2015 0927	25.21	10.6	32.3	0.078	23.7	18.9	0	0	1	0	0	0.33	2.8	3.95	6.2
1589440	2017 0404	25.21	10.6	32.3	0.078	23.7	18.9	0	0	1	0	0	0.49	1.4	2.95	5.3
1589500	2012 1027	5.04	4.7	31.3	0.036	28.8	33.5	0	1	0	0	0	1.32	5.1	13.25	19
1591000	2012 0707	34.95	13.2	29.8	0.092	42.1	3.9	0.2	0	1	0	0	0.44	7.6	7.15	9.6
1591000	2012 1027	34.95	13.2	29.8	0.092	42.1	3.9	0.2	0	1	0	0	2.09	7.2	11.1	15.1
1591000	2013 0129	34.95	13.2	29.8	0.092	42.1	3.9	0.2	0	1	0	0	1.71	10.2	5.3	6.9
1591000	2015 0625	34.95	13.2	29.8	0.092	42.1	3.9	0.2	0	1	0	0	0.62	3.7	4.4	6.6
1591000	2016 0730	34.95	13.2	29.8	0.092	42.1	3.9	0.2	0	1	0	0	0.72	4.5	3.55	5.1
1591400	2013 0129	22.86	9.6	32.3	0.08	22.8	8.3	0.2	0	1	0	0	1.42	4.2	3.5	5.1
1591400	2015 0624	22.86	9.6	32.3	0.08	22.8	8.3	0.2	0	1	0	0	0.83	2.5	3.5	5.6
1591400	2016 0729	22.86	9.6	32.3	0.08	22.8	8.3	0.2	0	1	0	0	0.69	3.1	2.85	4.4
1591700	2015 0626	27.31	11.2	26.5	0.056	32.8	11.5	0.4	0	1	0	0	0.85	2.8	5.2	8.2
1591700	2016 0729	27.31	11.2	26.5	0.056	32.8	11.5	0.4	0	1	0	0	0.59	11.8	6.6	8.4
1593500	2016 0729	38.1	17.3	18.8	0.053	19.5	31.2	0.6	0	1	0	0	1.83	6.7	7.15	9.8
1594000	2012 1027	98.25	25	14	0.059	24	21.5	0.3	1	0	0	0	2.76	9.8	11.85	15.5
1594000	2015 0624	98.25	25	14	0.059	24	21.5	0.3	1	0	0	0	0.85	3	6.25	9.8

Station	Date	DA	L	CS	LS	FOR	IA	ST	CP	PM	BR	AP	DRO	m	tpeak UH	tinfl UH
1594526	2012 1027	89.38	20.3	7.7	0.055	33	24.6	0.3	1	0	0	0	1.91	3.4	18.95	29.1
1596500	2014 0511	48.53	20.9	62.5	0.22802	78.8	1.3	0.4	0	0	0	1	0.77	5.4	12.6	17.9
1599000	2012 1027	72.74	19.6	58.5	0.17098	71.4	4.2	0	0	0	0	1	0.86	0.1	1	4.1
1617800	2012 1027	18.34	10.1	25.5	0.035	14.7	9.2	0.1	0	0	1	0	0.15	2.4	11.75	19.2
1617800	2018 0816	18.34	10.1	25.5	0.035	14.7	9.2	0.1	0	0	1	0	0.11	1.3	6.75	12.6
1637500	2012 1027	67.33	25.3	45.6	0.124	45.2	6.1	0	0	0	1	0	2.95	8.3	10.8	14.4
1639140	2012 1027	31.37	16.76	17.8	0.0484	15.1	2.5	1.9	0	0	1	0	3.39	4.2	12.95	19.2
1643500	2015 0928	62.94	18.4	29.6	0.103	41.7	6.4	0.1	0	0	1	0	0.27	0.7	1.55	3.3
1643500	2016 0727	62.94	18.4	29.6	0.103	41.7	6.4	0.1	0	0	1	0	0.51	4.8	4.7	6.7
1644371	2013 0608	0.42	1.32	126.8	0.068	23.5	28	0	0	1	0	0	0.8	3.7	0.45	0.6
1644371	2016 0729	0.42	1.32	126.8	0.068	23.5	28	0	0	1	0	0	1.32	1.8	0.325	0.5
1644372	2016 0729	0.34	1.26	112.77	0.06069	28.8	1.6	0	0	1	0	0	1.33	3.6	0.575	0.8
1644375	2013 0608	1.29	2.45	63.1	0.043	8.6	53.5	0.1	0	1	0	0	0.76	1.1	0.55	1
1649500	2012 1027	73.2	17.8	27.5	0.055	28.8	28.3	0.2	1	0	0	0	1.86	2	6.4	10.8
1649500	2014 0609	73.2	17.8	27.5	0.055	28.8	28.3	0.2	1	0	0	0	0.31	1	0.65	1.2
1658000	2014 0427	55.57	20.7	9.9	0.034	51.4	15.3	0.1	1	0	0	0	0.95	0.7	9.9	21.6
1658000	2018 1009	55.57	20.7	9.9	0.034	51.4	15.3	0.1	1	0	0	0	2.03	4.9	16.7	24.1
1660920	2014 0427	81.61	19.3	9.2	0.044	58	9.2	0.2	1	0	0	0	1.85	5.9	26.4	37.2
1484713 20	2012 1026	6.38	5.01	2.5	0.00619	30.2	0.9	0	1	0	0	0	4.75	0.5	2.55	6.1



**Table 6. Correlation Structure of Predictor and Response Variables**

		Predictors												Response		
		DA	L	CS	LS	FOR	IA	ST	CP	PM	BR	AP	DRO	m	tpeak UH	tinfl UH
Predictors	DA	1.000														
	L	0.919	1.000													
	CS	-0.337	-0.401	1.000												
	LS	0.302	0.388	0.400	1.000											
	FOR	0.303	0.289	0.191	0.372	1.000										
	IA	-0.118	-0.138	0.268	0.005	-0.437	1.000									
	ST	-0.193	-0.228	-0.174	-0.273	-0.091	-0.173	1.000								
	CP	0.114	-0.031	-0.498	-0.681	0.069	-0.261	0.288	1.000							
	PM	-0.230	-0.130	0.456	0.405	-0.192	0.369	-0.243	-0.812	1.000						
	BR	0.128	0.188	-0.044	0.107	-0.020	-0.152	-0.041	-0.197	-0.326	1.000					
	AP	0.171	0.193	0.129	0.596	0.439	-0.132	-0.030	-0.111	-0.183	-0.044	1.000				
	DRO	0.113	0.112	-0.185	-0.162	-0.046	0.044	-0.051	0.195	-0.171	0.010	-0.065	1.000			
Response	m	0.097	0.080	-0.043	0.072	-0.048	0.092	0.001	-0.133	0.176	-0.049	-0.076	0.103	1.000		
	tpeak UH	0.340	0.259	-0.475	-0.378	0.317	-0.281	0.109	0.570	-0.561	0.041	-0.006	0.230	0.209	1.000	
	tinfl UH	0.330	0.253	-0.496	-0.407	0.320	-0.290	0.114	0.607	-0.605	0.051	0.004	0.238	0.120	0.991	1.000

Note: Colors denote |correlation| > 0.3, yellow = positive, orange = negative

### Stepwise Regression Results

#### *Gamma Unit Hydrograph m Parameter / Peak Rate Factor*

Stepwise regression analysis of the log gamma *m* parameter, including all rows of Table 5, identified only one significant predictor, the Appalachian Plateau index:

$$\log m = 0.49932 - 0.633123 AP \quad (\text{Eq. 9})$$

Equivalently, the best estimate of gamma *m* based on these data is a constant value for non-Appalachian Plateau watersheds (*AP* = 0):

$$m = 10^{0.49932} = 3.157 \quad (\text{Eq. 10})$$

and for Appalachian Plateau watersheds

$$m = 10^{(0.49932-0.633123)} = 0.735 \quad (\text{Eq. 11})$$

These values of *m* correspond to PRF of 445 and 198, respectively. The standard error is 105%.

When only the Coastal Plain entries were analyzed, stepwise regression returned a constant model,

$$\log m = 0.448246 \quad (\text{Eq. 12})$$

$$m = 10^{0.448246} = 2.807 \quad (\text{Eq. 13})$$

This value corresponds to a PRF of 418, which is considerably higher than the 284 PRF associated with the Delmarva DUH. The standard error is 92.3%.

Finally, the regression was run excluding the Coastal Plain entries. Both the Appalachian Plateau index variable and log of DRO were identified as significant,

$$\log m = 0.557053 - 0.661876 AP + 0.323558 (\log DRO) \quad (\text{Eq. 14})$$

or

$$\log m = 3.606 AP^{-0.661876} DRO^{0.323558} \quad (\text{Eq. 15})$$

The standard error is 107.4%. This result is the only instance where we observed DRO entering a regression model.

Overall, the large standard errors of these models indicate that the gamma  $m$  parameter – and consequently the PRF – are not successfully predicted with the selected watershed properties.

### ***Gamma Unit Hydrograph Time of Concentration***

Stepwise regression analysis of the  $\log_{10}(\text{tinfl})$ , the variable which we chose as best representative of  $T_c$ , identified four significant predictors, Channel Slope, Land Slope, Forest, and Blue Ridge Province index:

$$\log_{10}(\text{tinfl}) = 4.13634 - 1.3597 \log_{10}(\text{CS}) + 0.512382 \log_{10}(\text{LS}) - 0.429388 \log_{10}(101 - \text{FOR}) + 0.256902 \text{BR} \quad (\text{Eq. 15})$$

or

$$t_{\text{infl}} = 13,688 \text{CS}^{-1.36} \text{LS}^{0.512} (101 - \text{FOR})^{-0.429} 10^{0.257 \text{BR}} \quad (\text{Eq. 16})$$

The standard error is 63.8%, which is twice the value of the SE associated with the Thomas (2000) regression for  $T_c$ . The results are shown in Figure 20. One outlier is noted (observed =

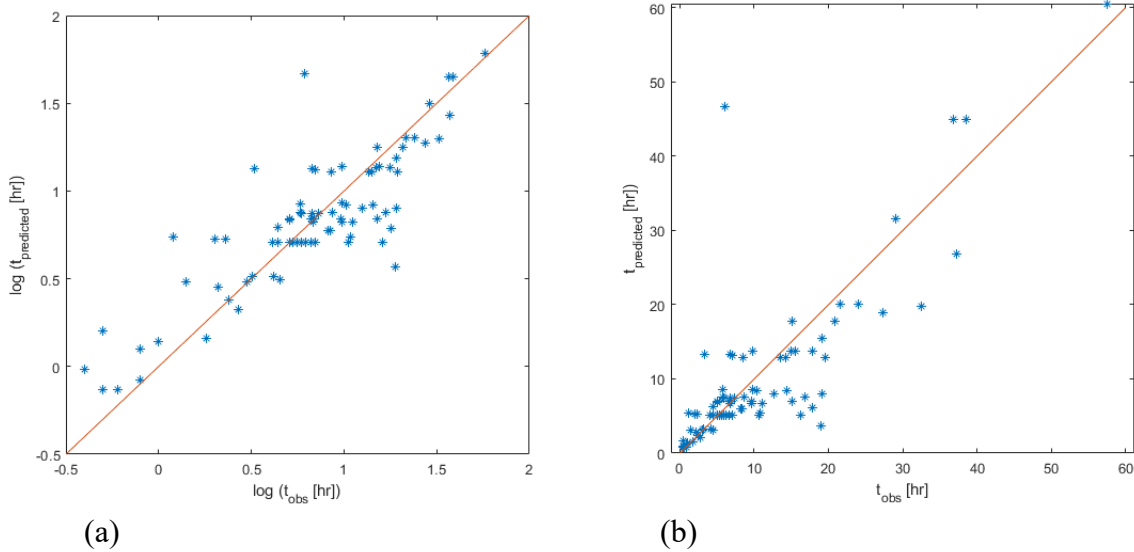


Figure 20. Stepwise Regression results for Time of concentration using the UH time to inflection ( $t_{inf}$ ). (a) Log, (b) dimensional [hr].

6.1 hr, predicted = 46.7 hr). This point is the last entry in Table 5, Station 148471320 on 20121026. This was a very heavy precipitation event (Hurricane Sandy) on a small watershed in the Coastal Plain. The other event on this watershed was excluded in the data censoring step. The combination of a negative exponent on Channel Slope (CS) and a positive exponent on Land Slope (LS) is puzzling, given that the two variables are positively correlated with each other and both negatively correlated with  $t_{inf}$

(Table 6). Figure 21 shows that the positive correlation between Channel Slope and Land Slope reflects a bifurcated pattern in the relationship between these two variables; in the Piedmont province, steep channels appear to be associated with less steep hillslopes. It is also surprising that the Blue Ridge Province index (BR) was significant in this model, given that it is nonzero for only 6 of the 82 input events.

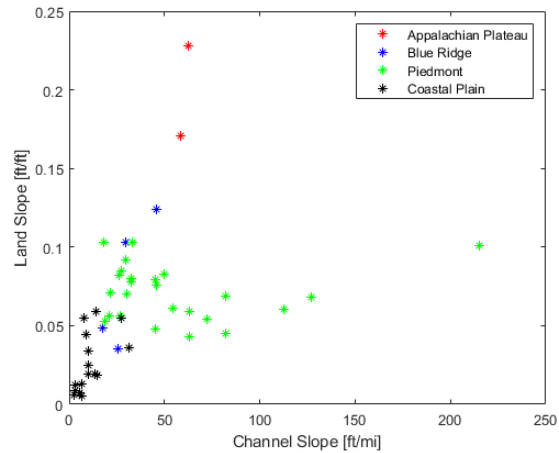


Figure 21. The relationship between Channel Slope and Land Slope shows a dual pattern of positive correlation.

The Time of Concentration regression described here was performed only on the new data collected and identified in the current study. The original expectation was that the former events and the current ones could be merged into a single, larger data set including more stream gages and covering a longer time period and a greater range of streamflow events. However, differences between the predictor variables used in the Thomas (2000) study (as inherited from Dillow [1998]) and those obtained for this study from HPR Appendix 1 and GISHydroNXT would need to be resolved.

### Relationship Between UH Time Variables

For the standard NRCS unit hydrograph, the ratio of  $t_{peak}$  to  $t_c$  is assumed to equal  $2/3$ , where  $t_c$  is defined as the inflection point on the UH recession (NRCS, 2010). The two time variables for all 82 events in the censored data set are shown as a scatter plot in Figure 22. The points cluster around the line  $t_{peak} = 2/3 t_{infl}$ . Figure 23 shows systematic variation in the ratio of  $t_{peak}$  to  $t_{infl}$  as a function of gamma shape parameter,  $m$ . The ratio is not purely a function of  $m$ , because it is a property of the dimensional UH and incorporates the magnitude of precipitation excess duration relative to  $t_{peak}$ . The red circle indicates the  $2/3$  ratio assumed in the NRCS curvilinear unit hydrograph with PRF 484.

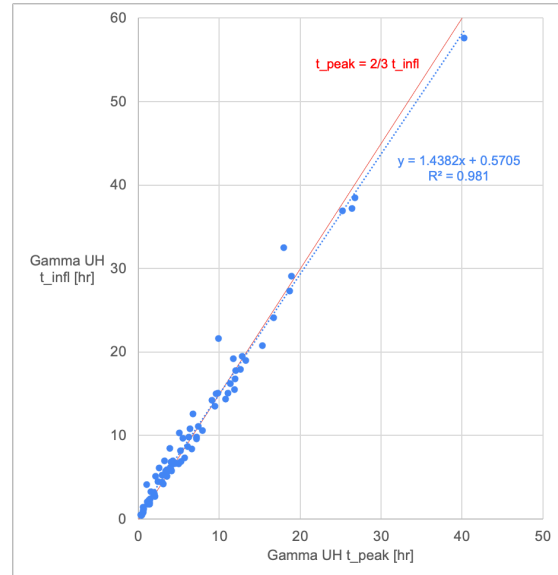


Figure 22. Gamma UH time to peak ( $t_{peak}$ ) and time between end of precipitation excess and mathematical inflection point on the receding limb ( $t_{infl}$ ). The blue dashed line is the linear regression; the red solid line indicates  $t_{peak} = 2/3 t_{infl}$ , analogous to the NRCS unit hydrograph assumption that  $t_p = 2/3 t_c$ .

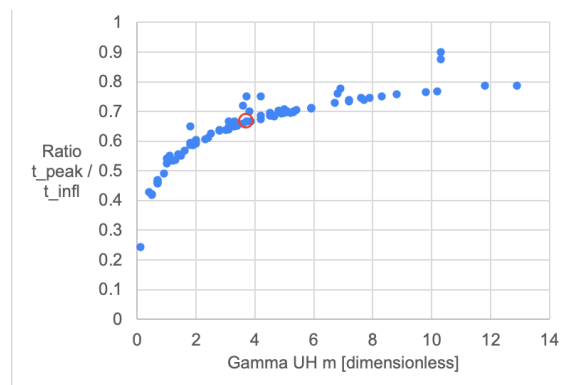


Figure 23. Ratio of time from end of precipitation excess to inflection point ( $t_{infl}$ ) to time to peak ( $t_{peak}$ ) with  $m$  parameter for Gamma UH identified for 82 events. The red circle indicates the assumed ratio of  $t_c$  to  $t_p$  ( $2/3$ ) for the NRCS unit hydrograph with PRF = 484 ( $m = 3.7$ ).

## Conclusions and Recommendations

A gamma unit hydrograph was identified for each of 100 events at 54 stations in Maryland. The  $m$  parameter of the gamma distribution and the time to peak of the unit hydrograph were selected as fundamental properties, rather than the PRF (which can be directly related to the  $m$  parameter mathematically). Of these events, 18 were excluded due to irrational results or low-quality fitting.

The gamma UH is defined by the dimensionless gamma  $m$  shape parameter and by time to peak,  $t_{peak}$  [hr]. The censored results, used in the analysis, had a range of gamma  $m$  from 0.1 to 12.9, which can be interpreted as a range of PRF from 48.8 to 919. This indicates that the shape of the unit hydrograph varies among watersheds, and possibly among events. However, very few systematic relationships were identified between selected watershed properties and the  $m$  parameter. An attempt to determine such dependence using stepwise log-linear regression indicates that the best estimate of an unknown gamma  $m$  is a constant between 3.04 and 4.11, corresponding to PRF 411 to 512. Independently estimated, this range encloses the currently accepted PRF 484. A preliminary screening also indicated no systematic relationship between event magnitude (as measured by direct runoff depth) and  $m$ . Insufficient event data were available to investigate variation with event magnitude for a given watershed.

The response time variable chosen to represent time of concentration is the time from end of precipitation excess to the mathematical inflection point on the (dimensional) gamma unit hydrograph ( $t_{infl}$ ). This time variable can be identified objectively using the equation of the gamma UH; it was shown to match well with expert-identified event  $T_c$  from a previous study. This response time varied among watersheds and among events for watersheds, over a range 0.5 to 57.6 hr in the censored data. A stepwise regression analysis identified three watershed variables as predictors of  $t_{infl}$ : channel slope, watershed slope, and forested area.

In this study,  $t_{infl}$  was analyzed as a surrogate for time of concentration,  $T_c$ . This decision was made for several reasons: First, the determination of  $T_c$  from an event hydrograph is highly

subjective. Although the hydrologic literature refers to an “inflection point” on the event hydrograph recession limb, that point is often interpreted as a change in slope, rather than the mathematical definition of “change in sign of the second derivative.” Because the hydrologic literature generally defines  $T_c$  as the time to end of direct runoff, we attempted to make this procedure more objective by calculating  $T_c$  as the time from end of Precipitation Excess to end of Direct Runoff, where the two endpoints were determined in a semi-automated process. We abandoned that measure of  $T_c$  and attempted to develop an equally objective method to determine  $T_c$  as the time from end of Precipitation Excess to the inflection point on the event hydrograph recession. That effort was only partially successful, as the inflection point occurred before the end of Precipitation Excess for many events, resulting in a negative  $T_c$ . Identifying and mathematically analyzing the unit hydrograph proved to be more robust. Second, we found that our  $t_{infl}$  was more consistent with previous estimates of  $T_c$  for study watersheds than was our event  $T_c$ .

The estimates of event  $T_c$ ,  $t_{infl}$ ,  $t_{peak}$ , and  $m$  are all subject to numerous sources of uncertainty that propagate through the procedures: bias in the NEXRAD precipitation; errors introduced by the simplistic baseflow and precipitation separation; and the timing of precipitation excess. Of the data sources used, it is reasonable to place the most confidence in the USGS streamflow measurement. The assumption of uniform rainfall over the watershed is also questionable for the larger basins during the long rainfall events associated with low probability discharge.

Although the NRCS segment velocity method is widely used to calculate  $T_c$ , we did not employ that method in this study. This decision was based on our interpretation of the velocity method as a tool to estimate watershed  $T_c$ , not as a definition or measurement of watershed  $T_c$ . Much of the hydrologic literature treats the velocity method as definition or measurement; however, that assumption is increasingly being questioned [e.g., Beven (2020), Grimaldi et al. (2012)].

This study developed analytical tools to generate a watershed-average hyetograph at fine temporal resolution using radar data and GIS. These tools released us from having to infer the hyetograph from sparse, remote precipitation gauges. We used an independent daily precipitation

data set to correct for unquantified bias in the radar fields; in some cases, this correction was a major shift, either positive or negative. In general, however, the pattern of daily precipitation was consistent. A deeper analysis of bias correction in the radar data would be a major undertaking.

The analysis tools also quantify the spatial variance of precipitation over the watershed. We did not make use of the spatial variance in this study. The UH approach assumes that precipitation is uniform over the watershed; this is well known to be a major simplifying assumption. Our radar data would allow us to evaluate how well or poorly the studied events satisfied that assumption. It is reasonable to expect that the assumption is better satisfied in small watersheds.

Convolved event hydrographs are sensitive to the shape of the UH, and consequently to the choice of gamma  $m$  (or PRF). Should the UH shape parameter (or PRF) be treated as a free tuning parameter in hydrologic modeling? If so, then analysts should keep in mind that both  $t_{peak}$  and  $m$  are required to generate a dimensional UH. If our  $t_{infl}$  can be accepted as a substitute for  $T_c$ , our results indicate that the ratio  $t_{peak}$  to  $T_c$  is not constant, but depends on  $m$ . Therefore, if analysts employ a different estimate of  $T_c$  for a watershed, while adjusting  $m$  or PRF, they should use an appropriate scaling ratio to obtain  $t_{peak}$  for their UH.

In this study, we invested substantial effort in developing methods to generate watershed event hyetographs from radar rainfall data. In contrast to the physical realism available in the hyetographs, the methods we applied for baseflow separation and precipitation excess are overly simplistic. Some events had to be discarded because the direct runoff inferred by baseflow separation was greater than the total precipitation supply; several of these occurrences were discovered when our algorithm reported a negative phi index. Future work should focus on applying hydrograph and hyetograph separation approaches that are conceptually appropriate, as physically accurate as possible within the assumptions of the UH approach, mutually consistent, and objective.

### **Recommendations for Practice**

1. The study indicates that PRF varies among watersheds. If practitioners apply alternatives to the standard PRF values, they should note that the proportionality between  $t_{peak}$  and  $t_c$  varies with PRF. They should not automatically apply the 2/3 ratio.
2. The current regression equation for  $T_c$  in Maryland (Thomas [2000]) should continue to be used.

### **Recommendations for Future Research**

1. Continue to develop tools for using radar rainfall to generate event hyetographs. Additional data sets should be investigated, including the hourly 4-km Stage IV product distributed by UCAR and the 4-km 1-hour accumulation DPA product distributed by NCEI, both of which could help to extend the study period back to 2000 or earlier.
2. Develop mutually compatible and physically accurate methods to separate streamflow and rainfall, while maintaining DRO equal to PEX for unit hydrograph identification.
3. Ensure compatibility among the predictor variables used at various times, e.g., Channel Length vs. Watershed Length.
4. Analyze the effect and implications of assuming  $UH t_p = 2/3 T_c$  when PRF is not equal to 484.
5. Slope variables are important in predicting  $T_c$ . Improvements on these estimates should be sought, particularly in the Coastal Plains province.
6. The different relationships between Channel Slope and Land Slope variables among the physiographic provinces is intriguing; examination of more watersheds' tabulated properties and the topography of Piedmont watersheds would reveal whether this is an artifact of sample size or a real physical phenomenon.



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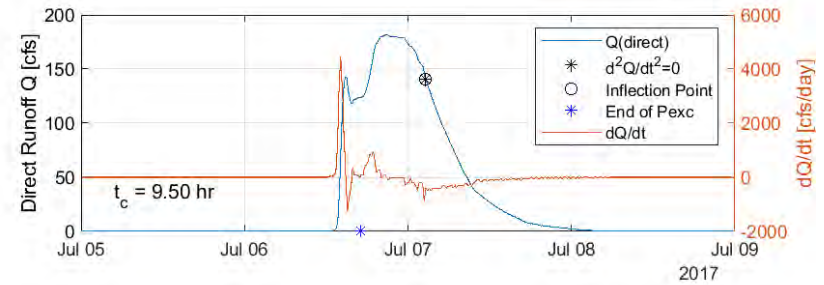
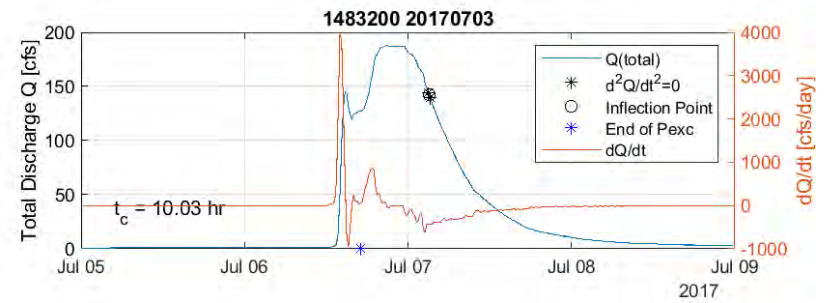
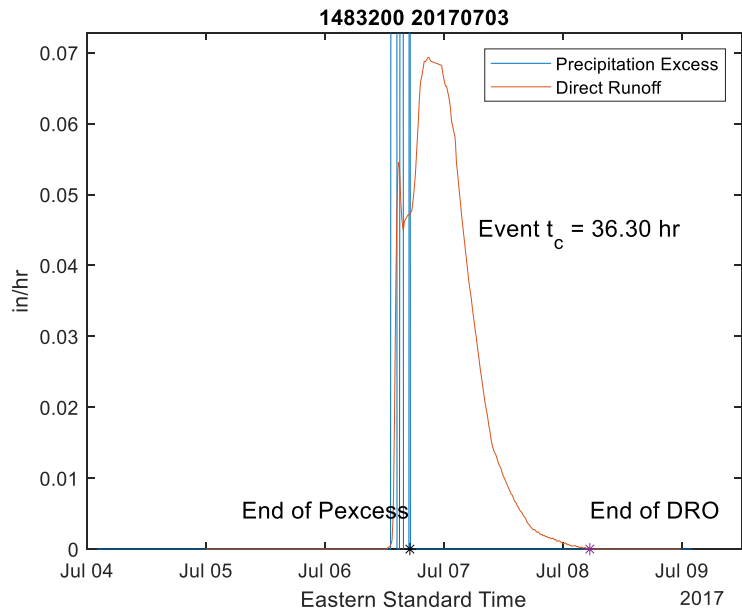
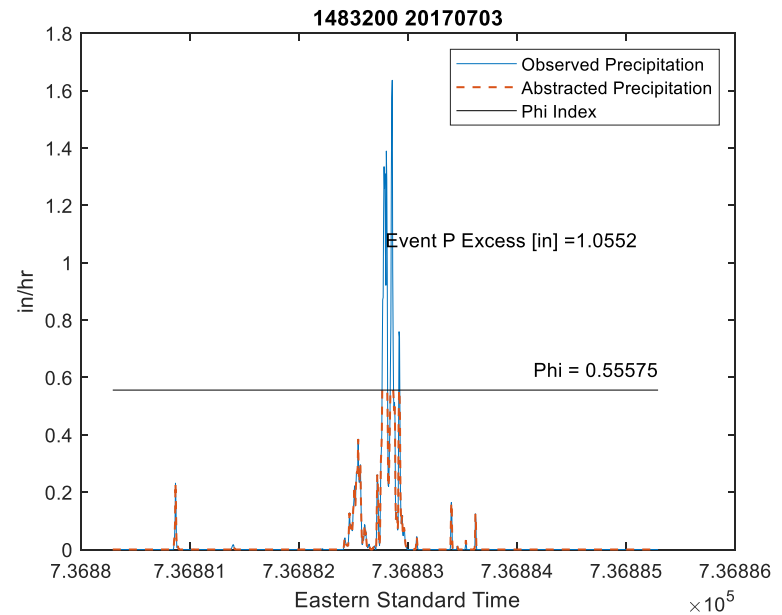
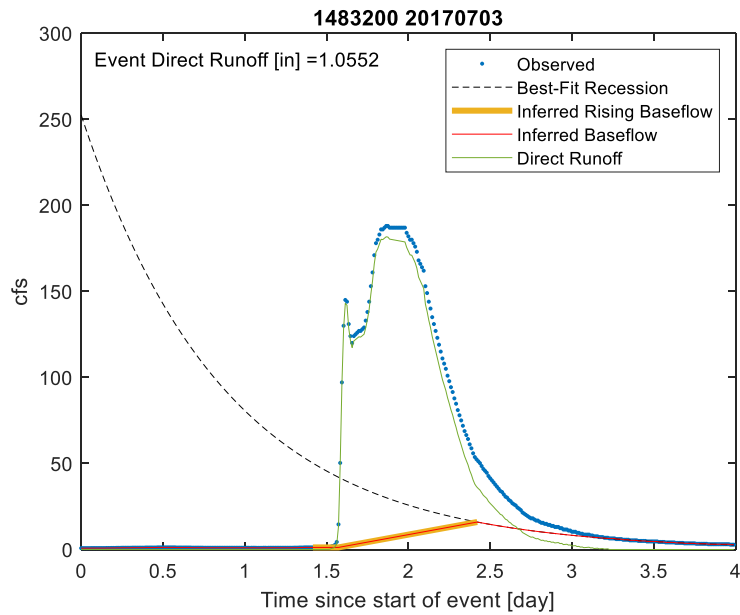
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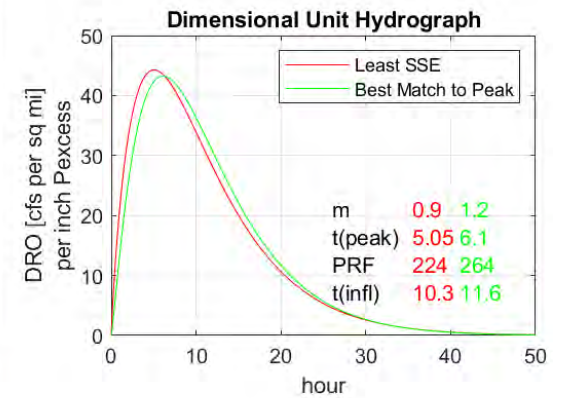
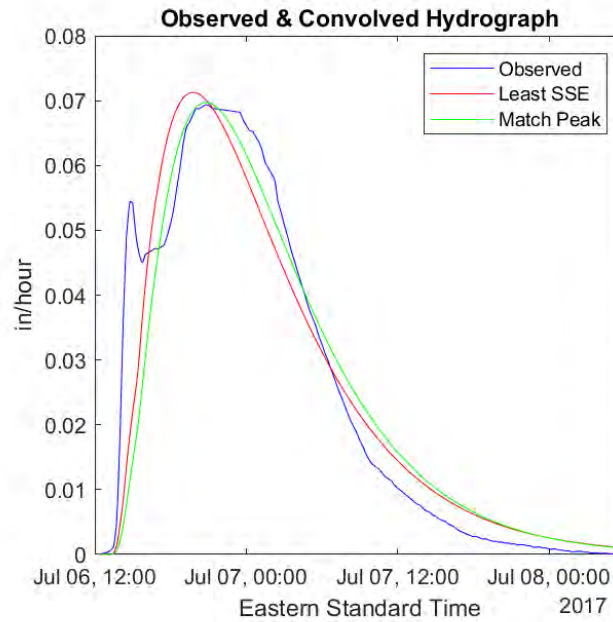
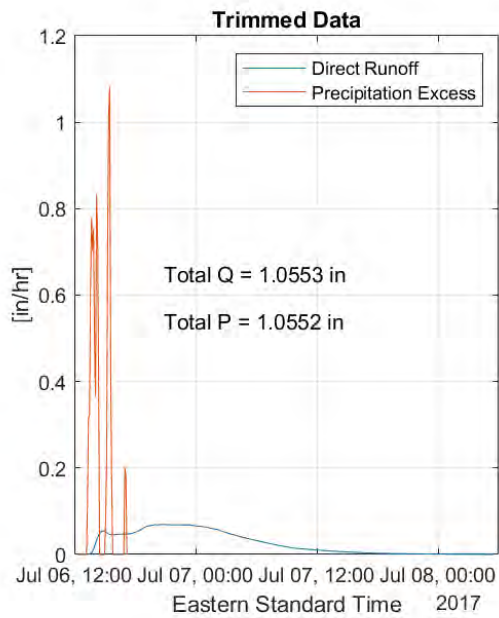
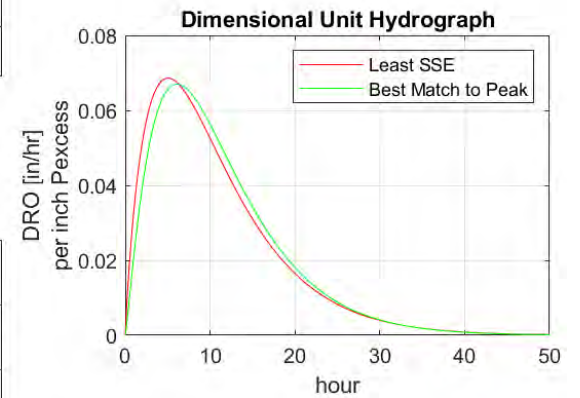
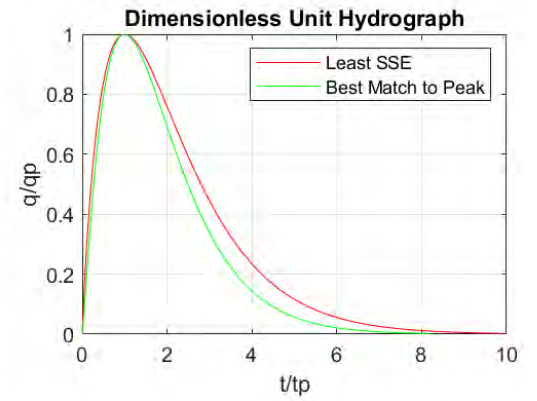
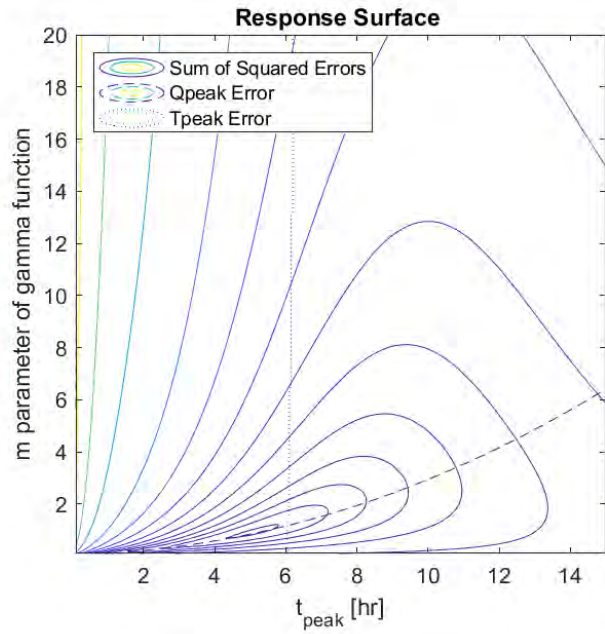
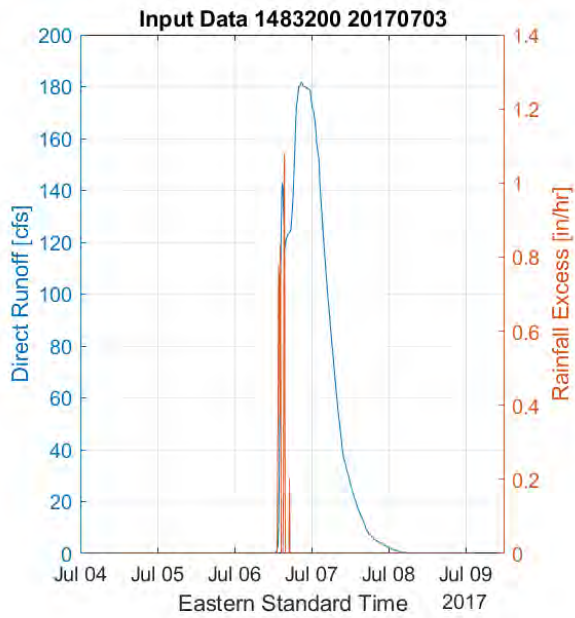
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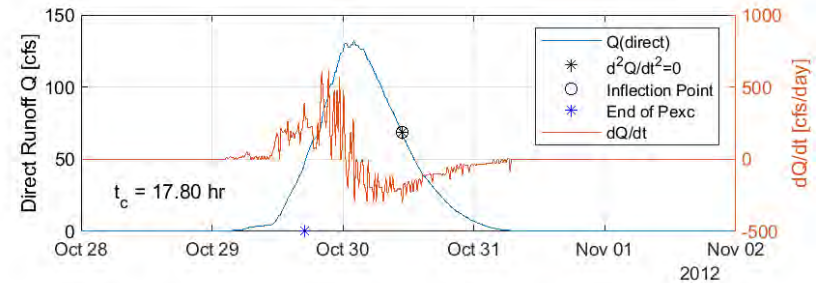
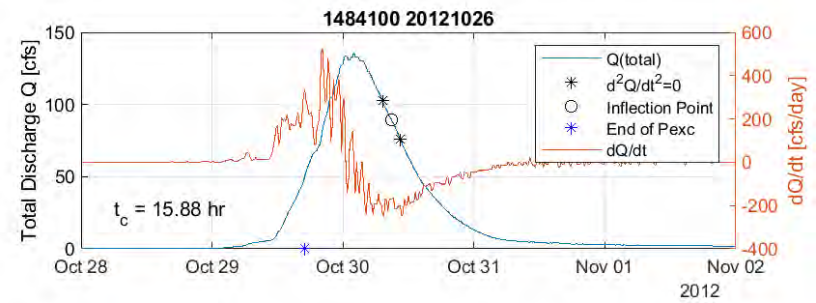
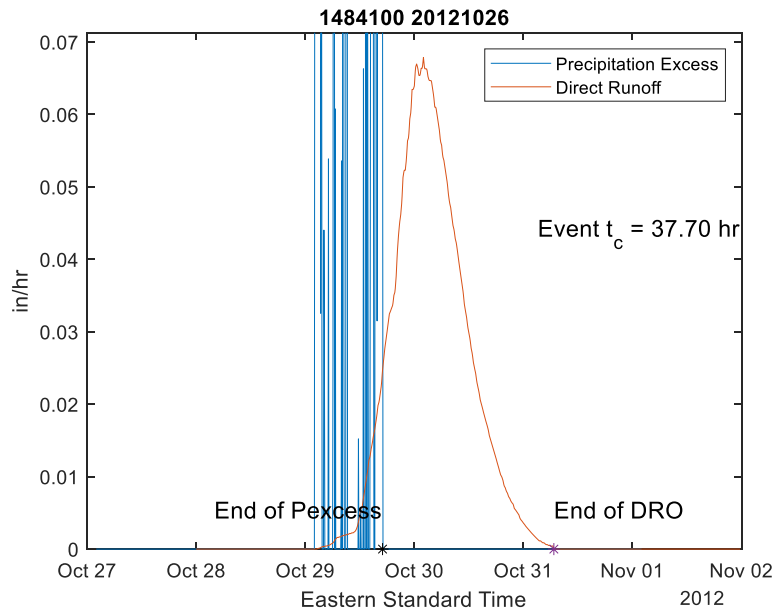
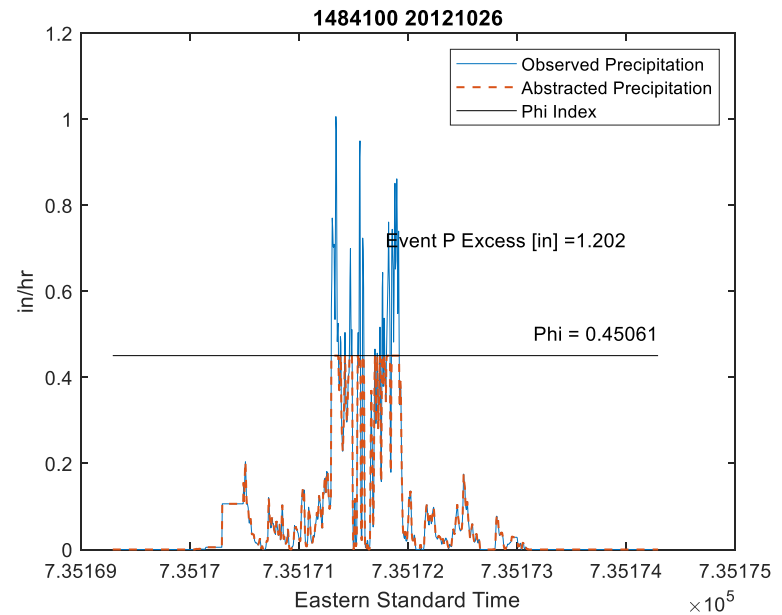
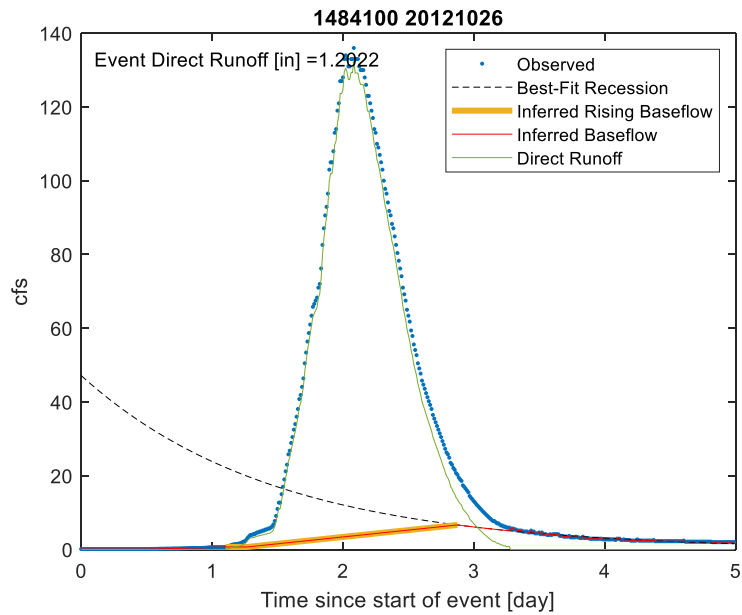
APPENDIX 1  
CATALOG OF UNIT HYDROGRAPH PROCESSING STEPS

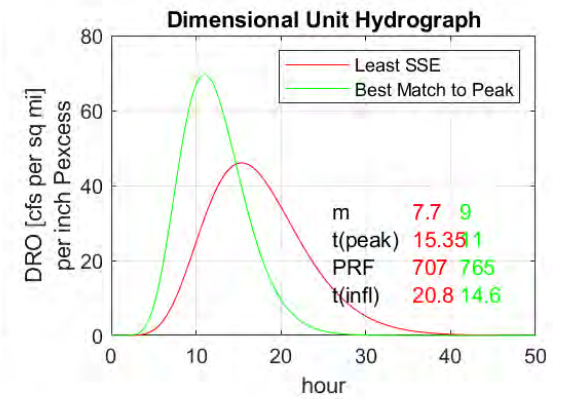
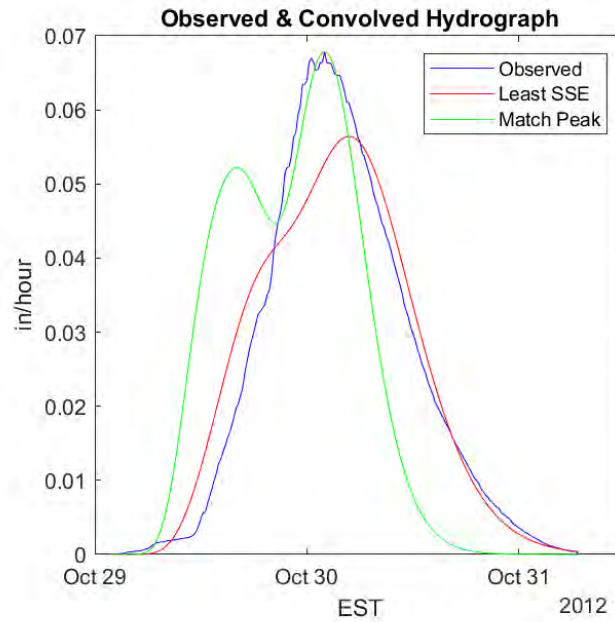
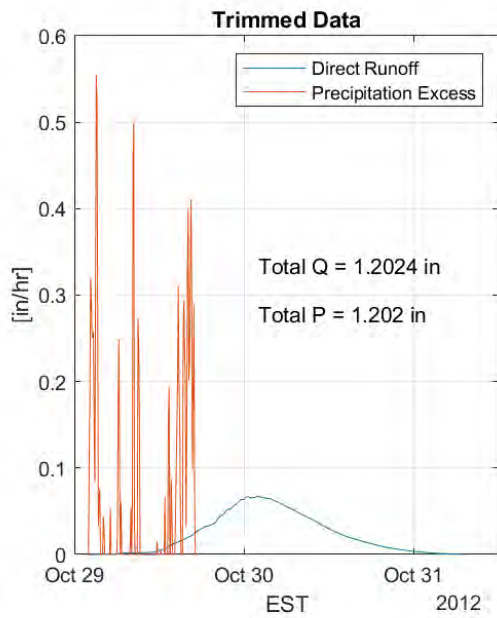
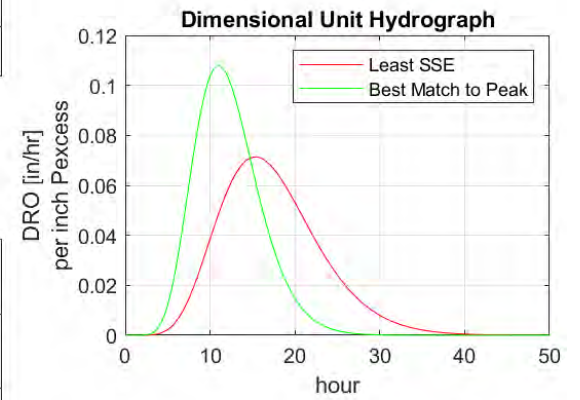
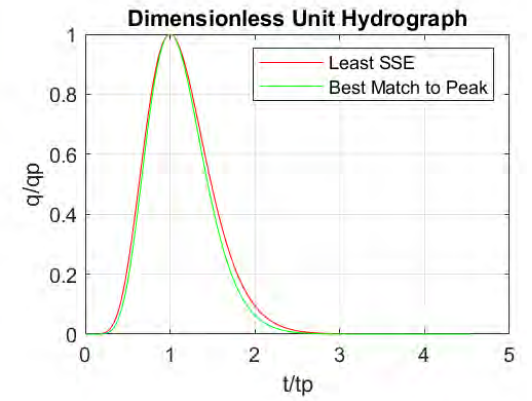
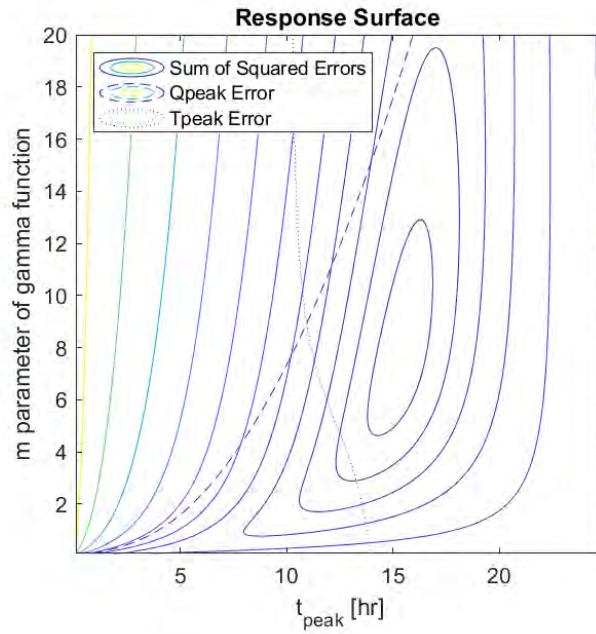
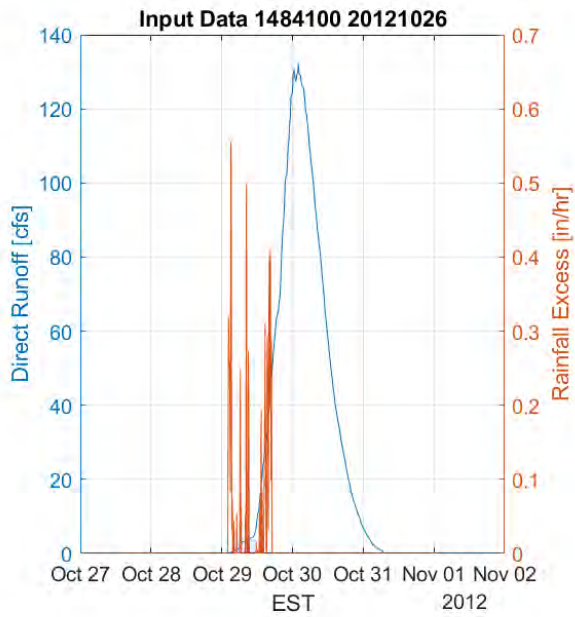
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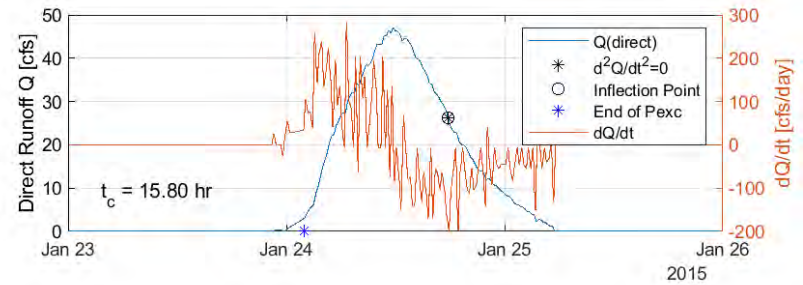
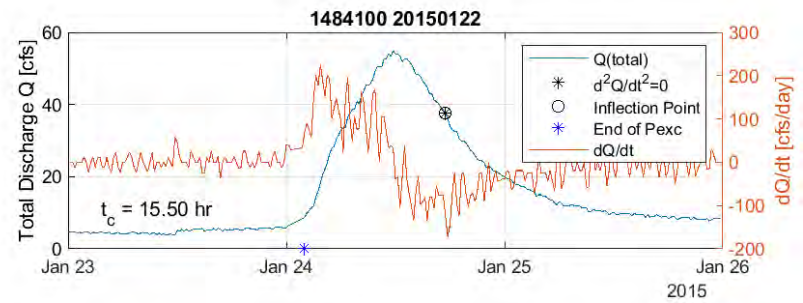
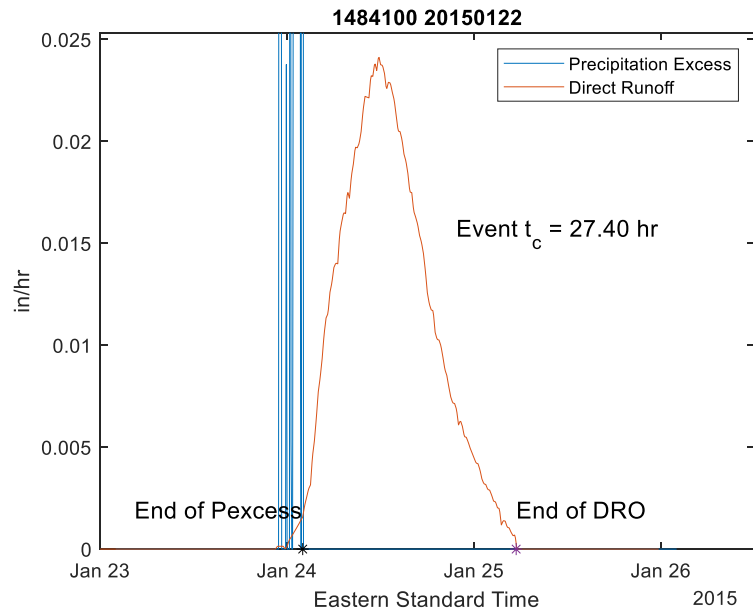
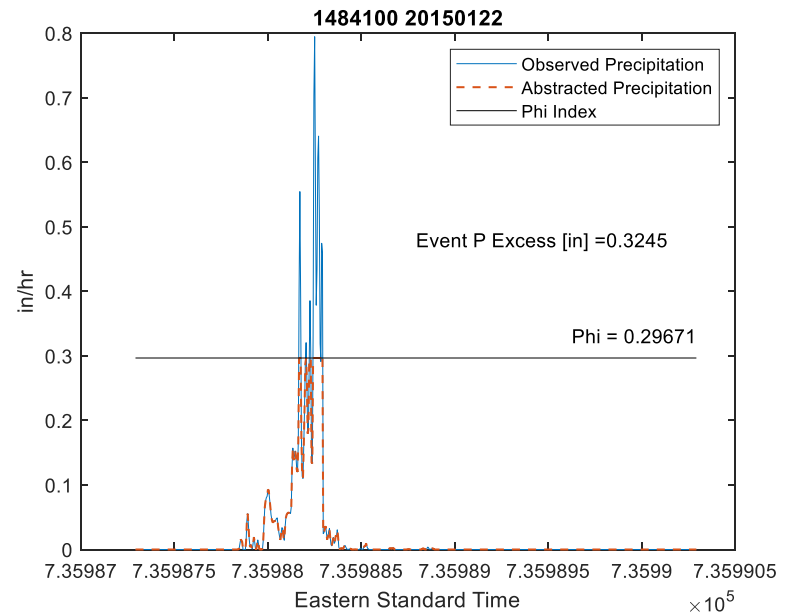
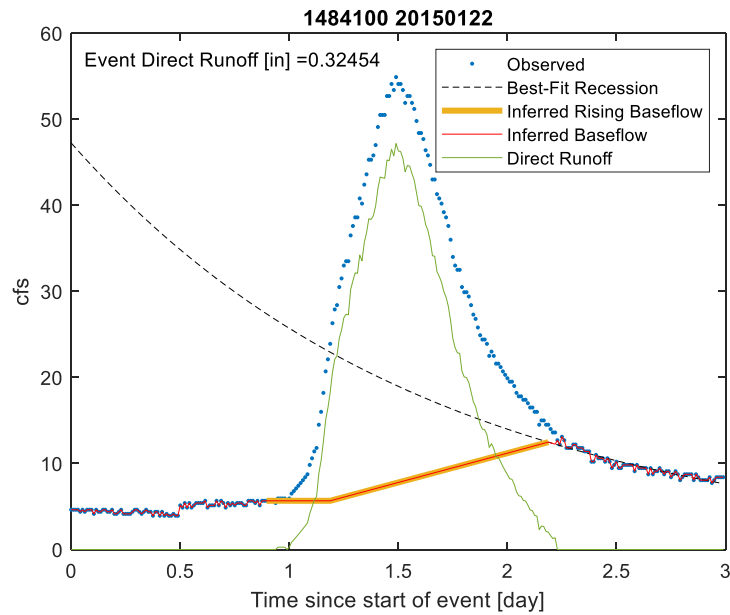
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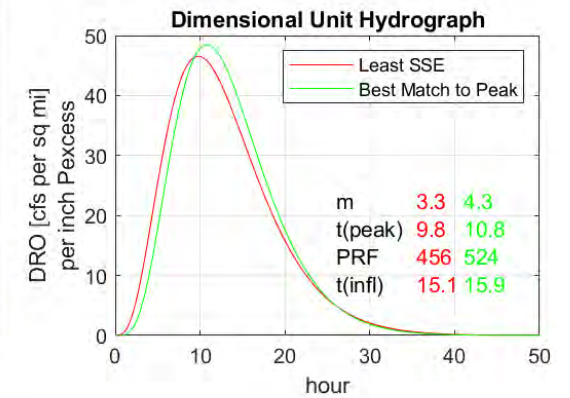
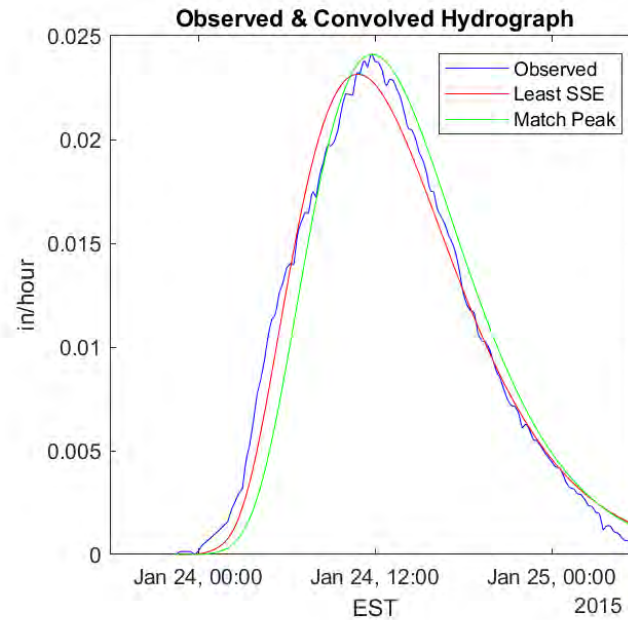
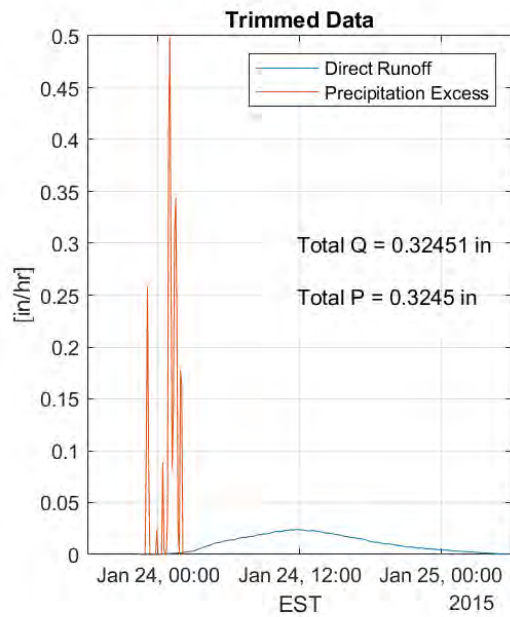
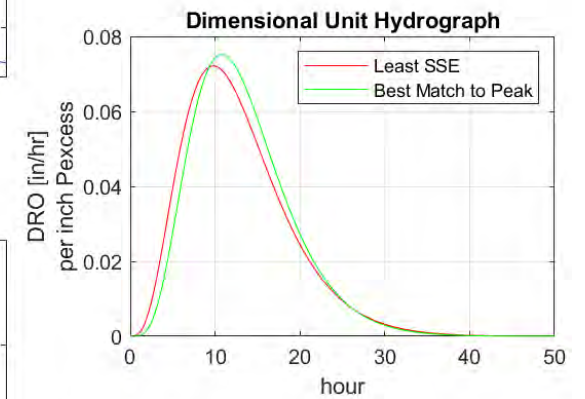
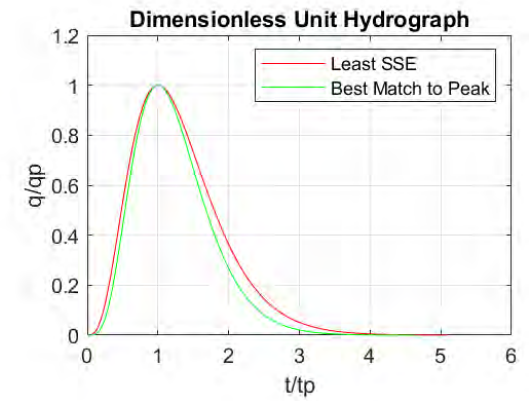
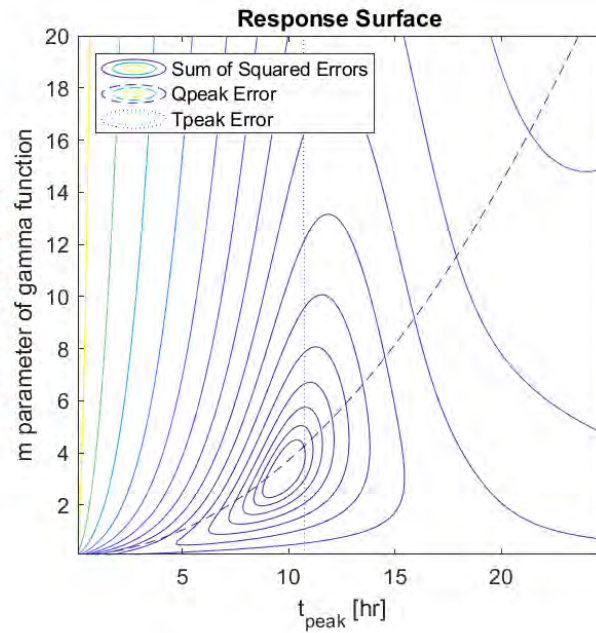
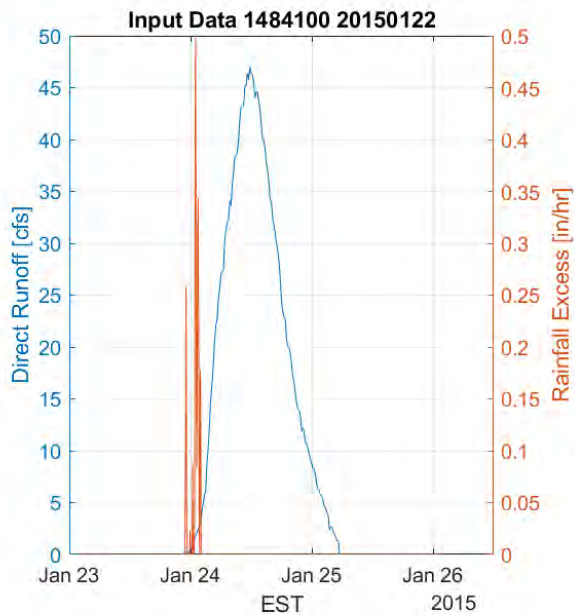


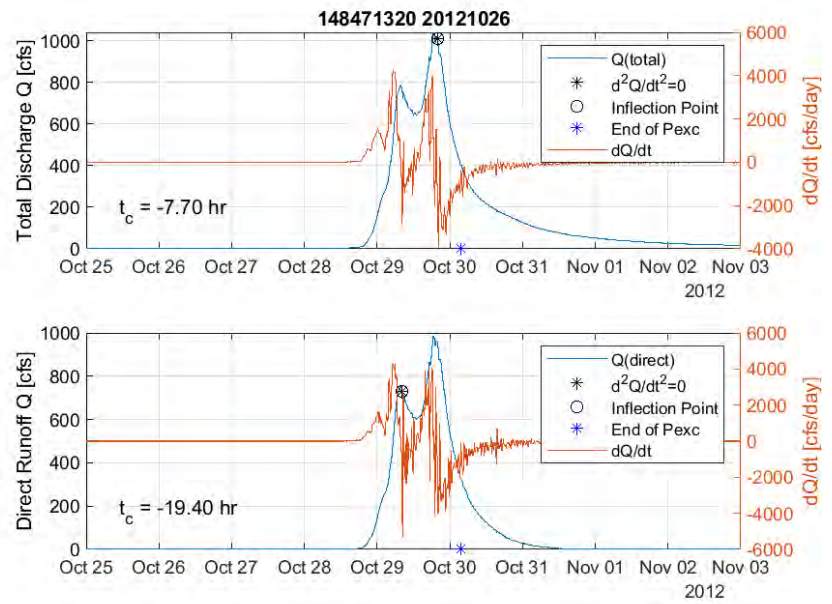
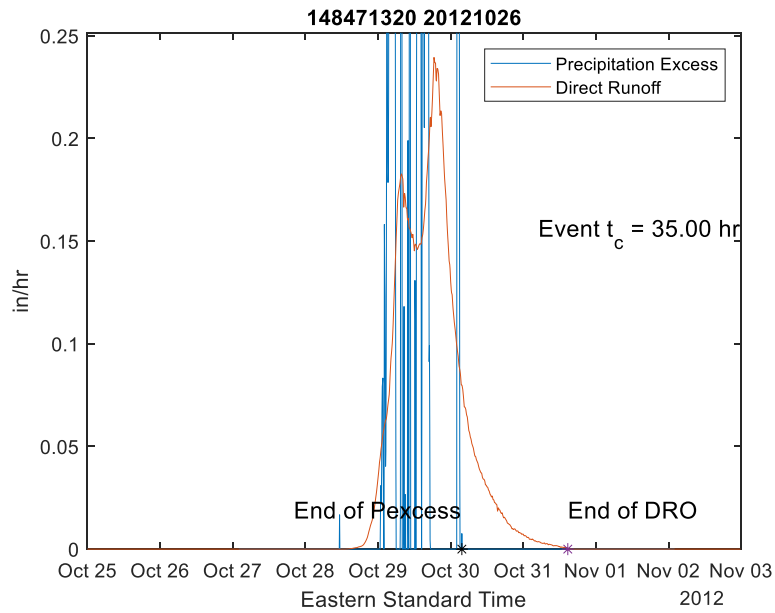
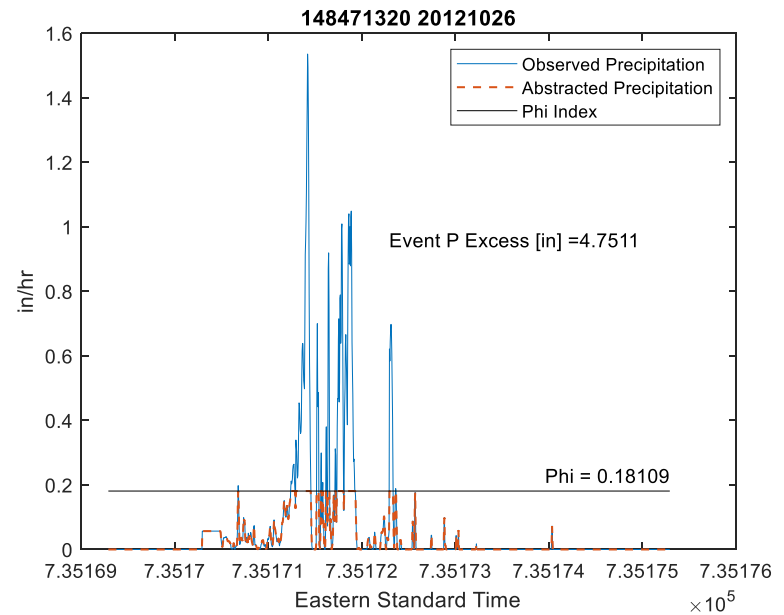
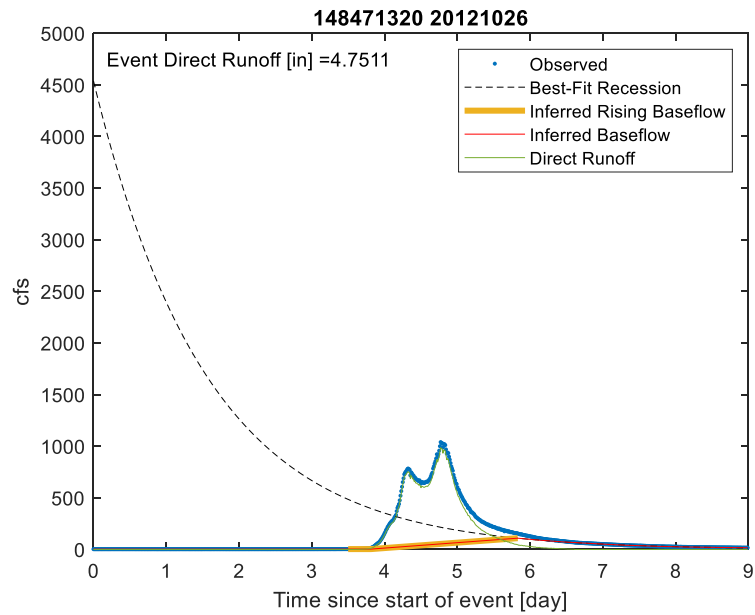


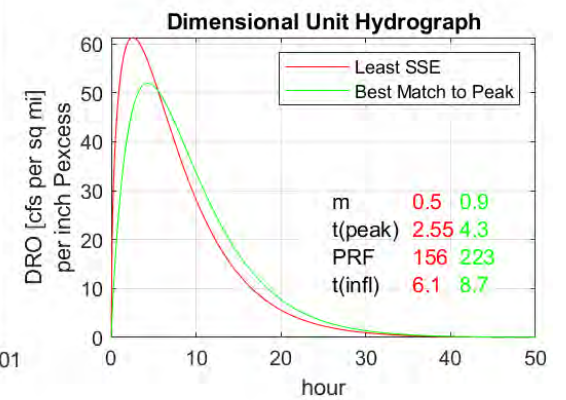
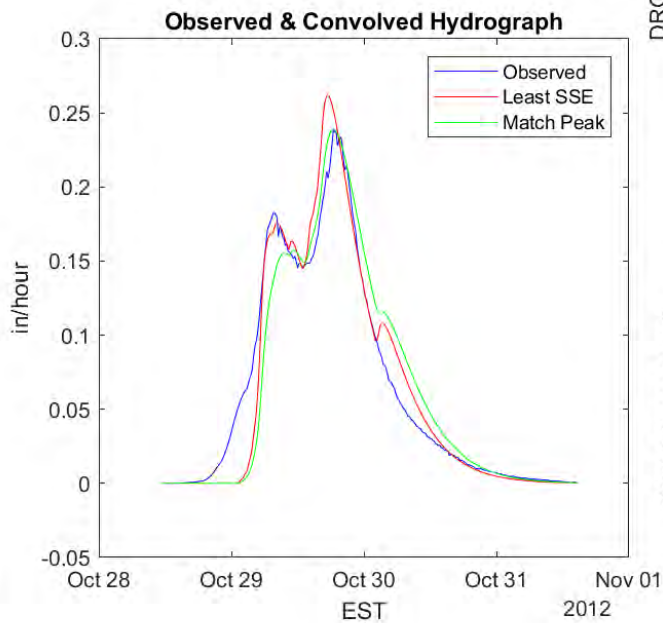
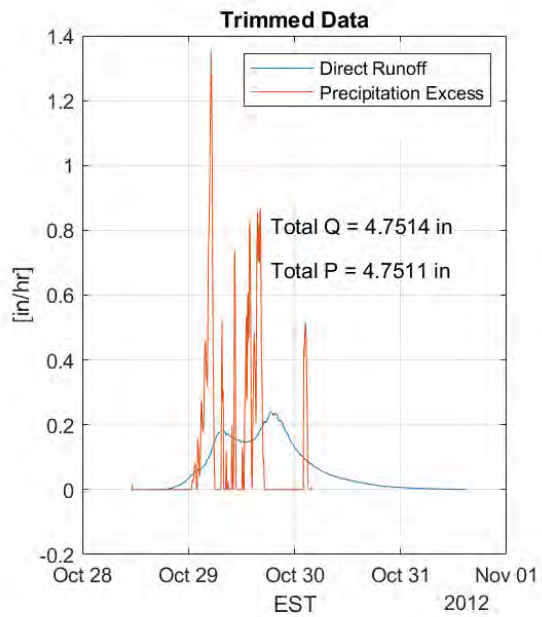
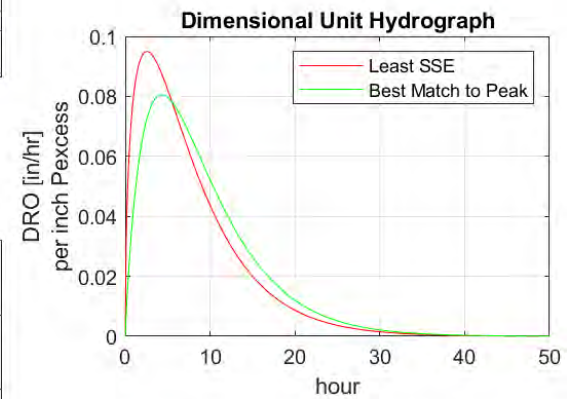
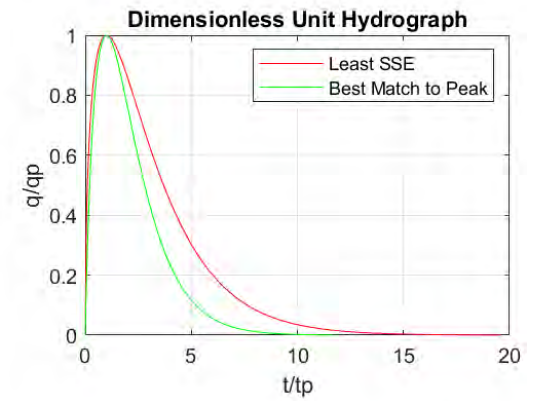
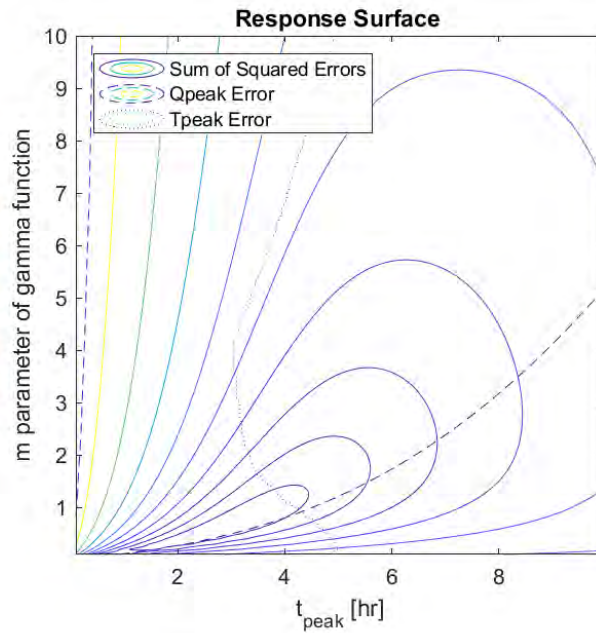
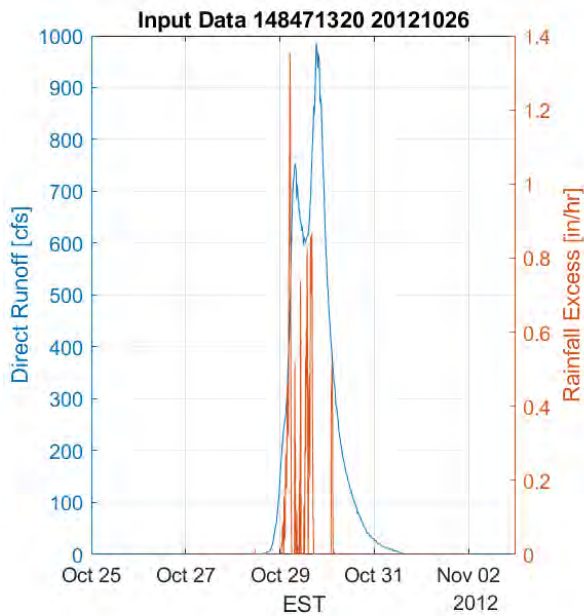


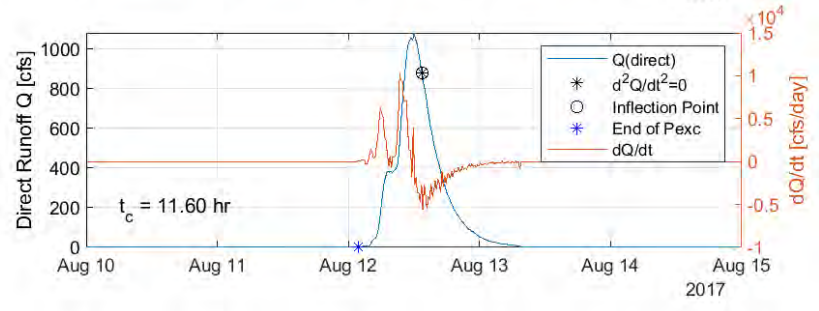
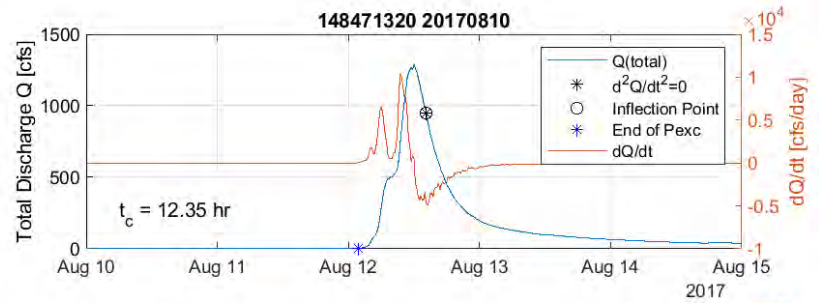
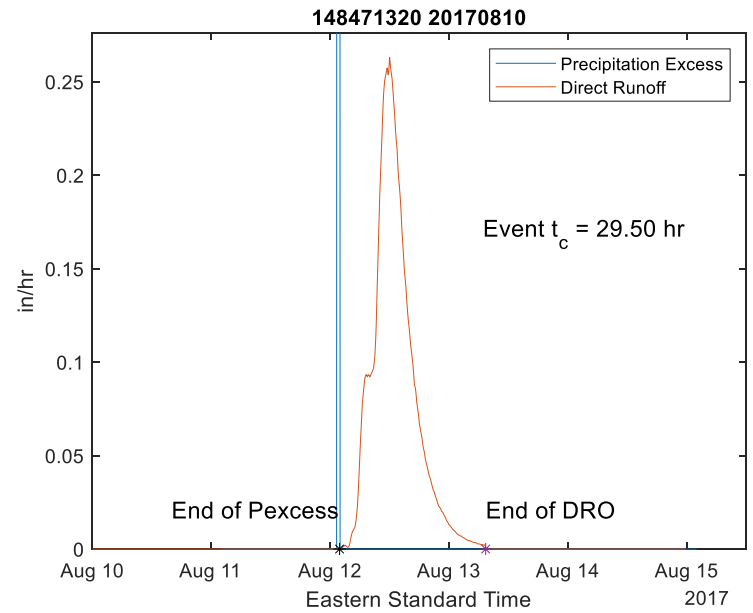
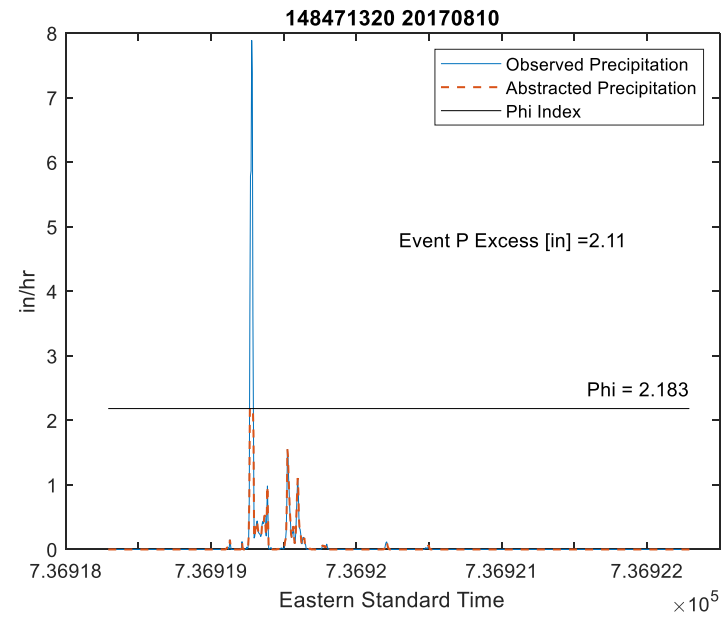
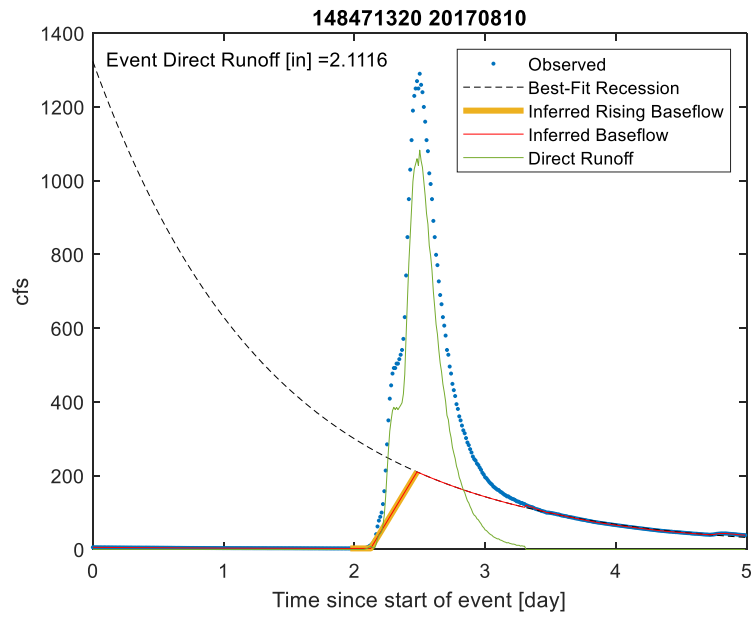


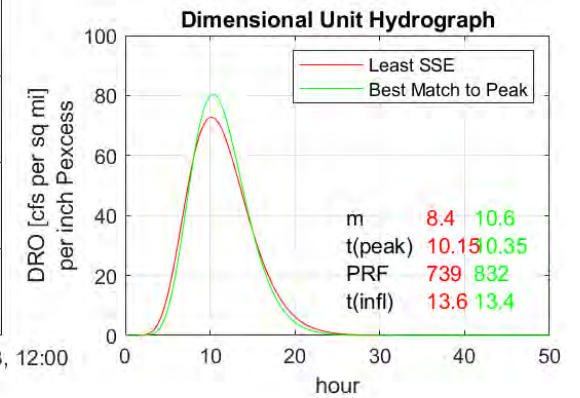
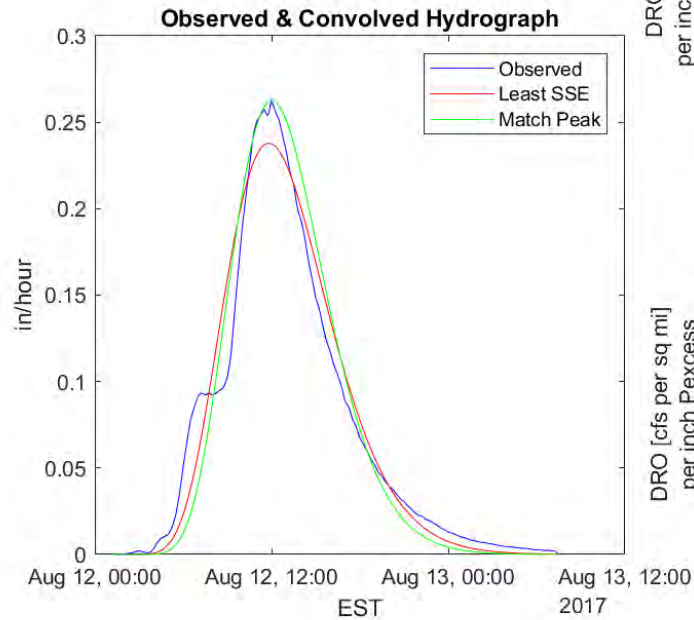
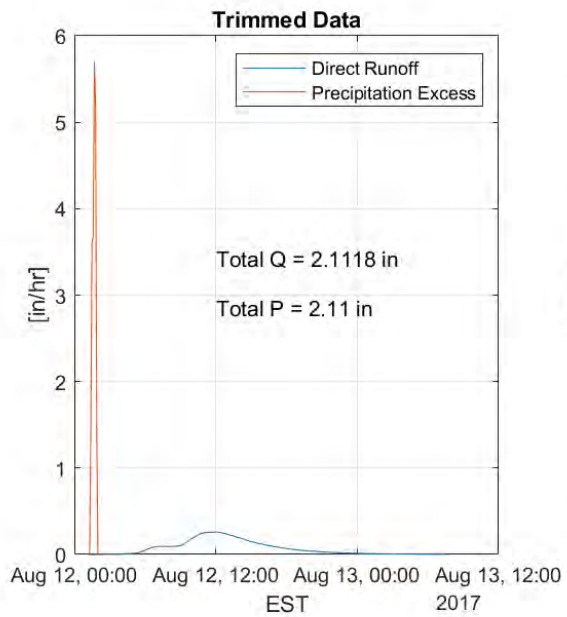
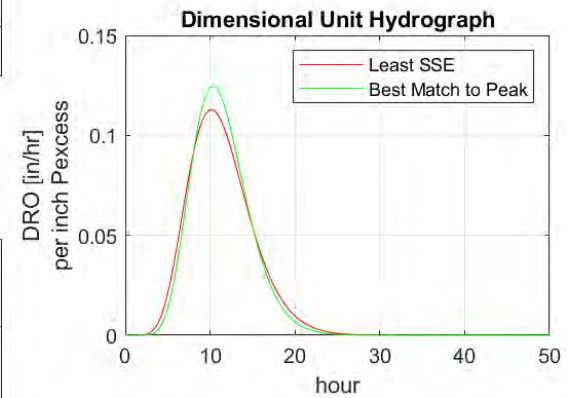
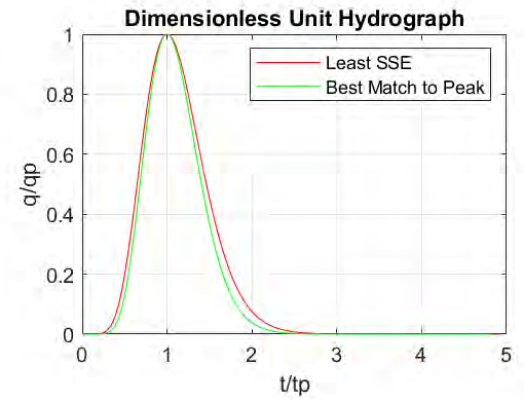
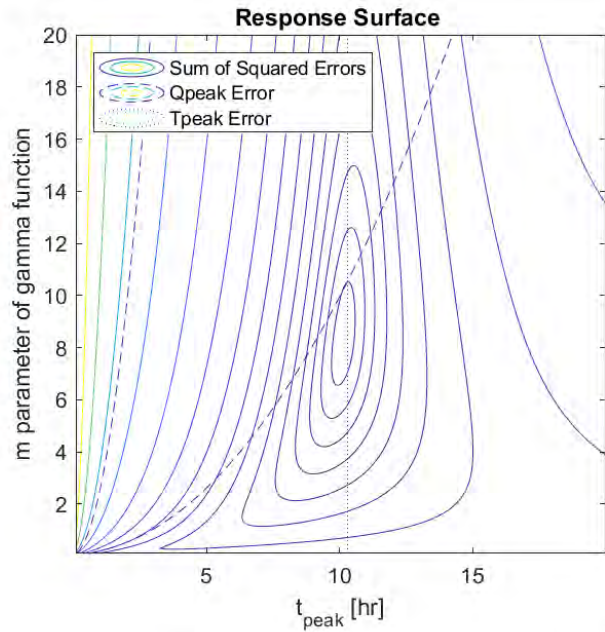
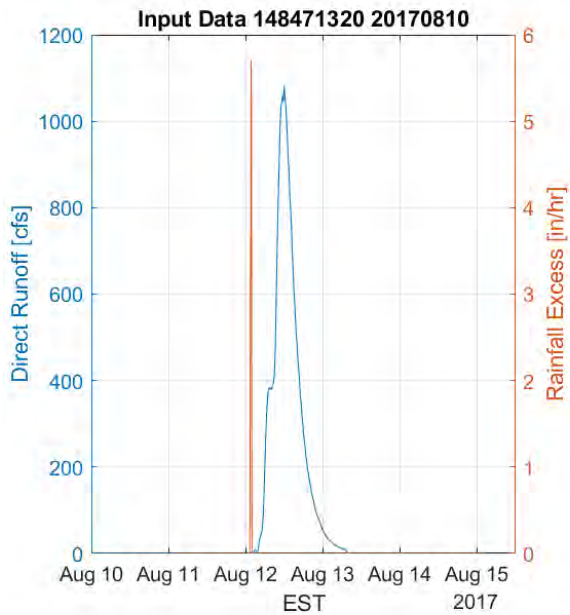


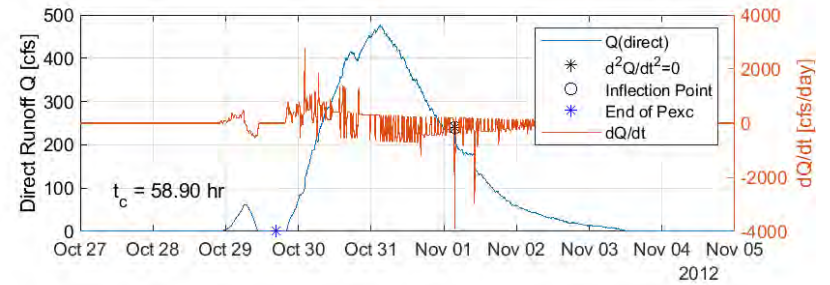
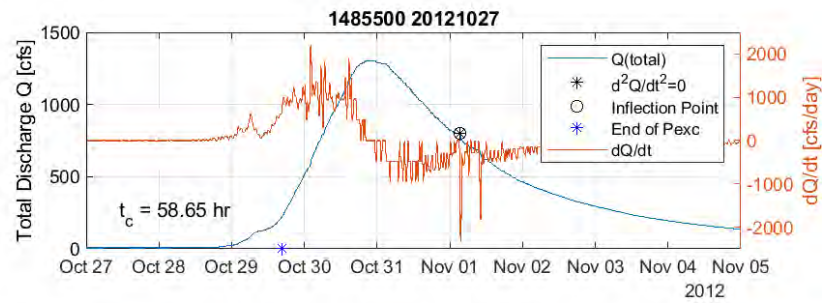
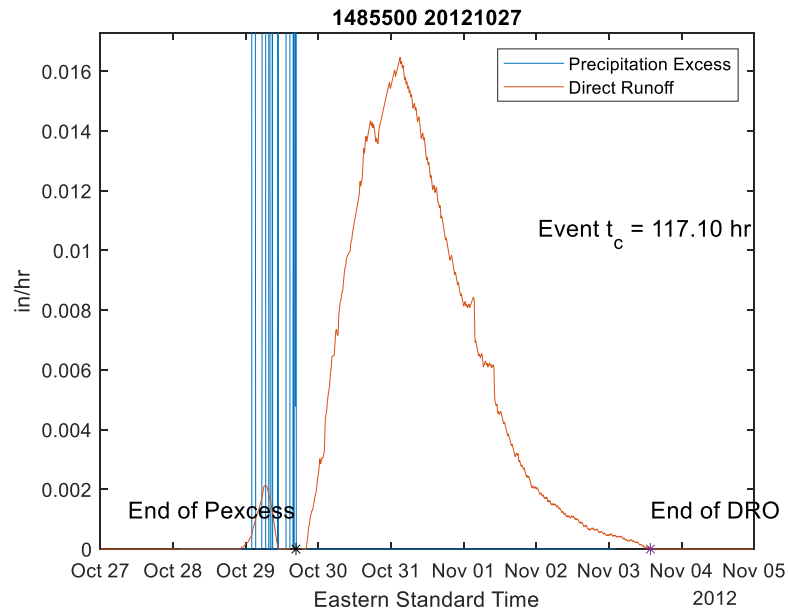
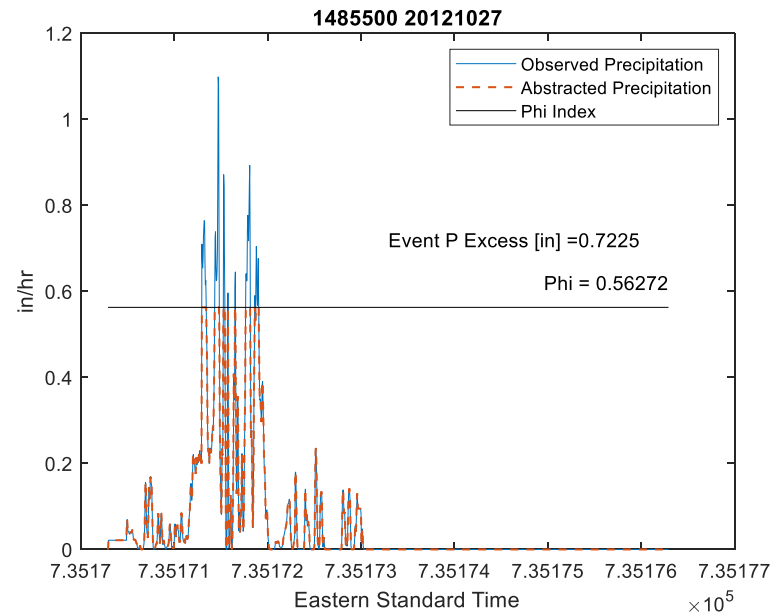
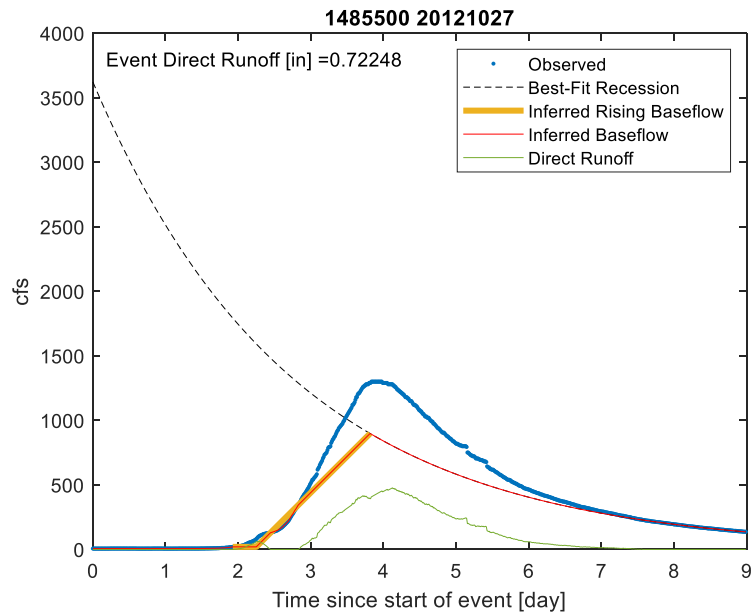


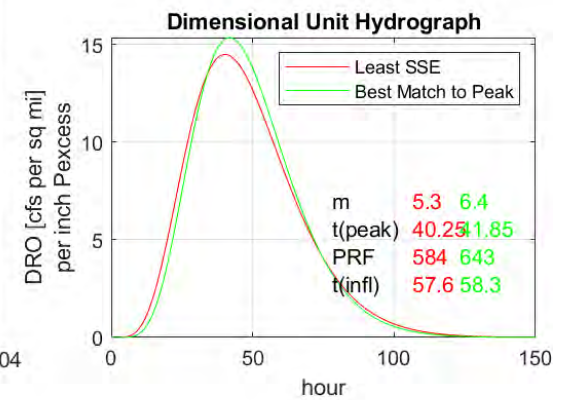
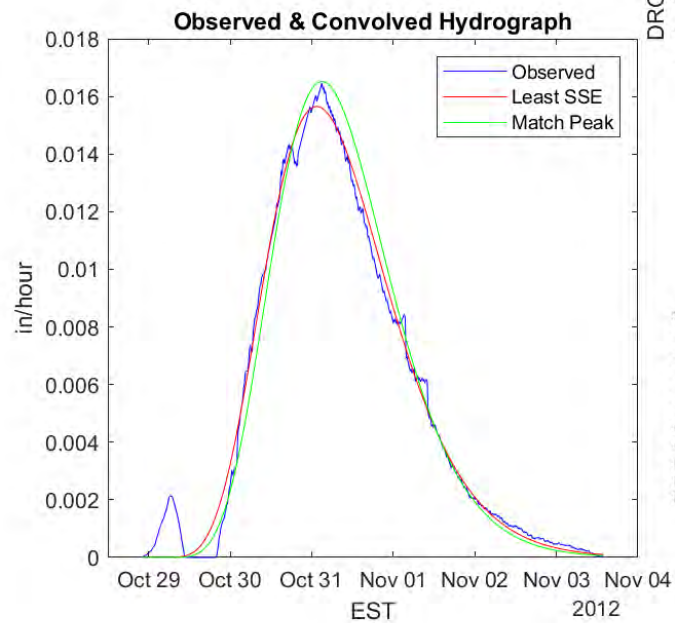
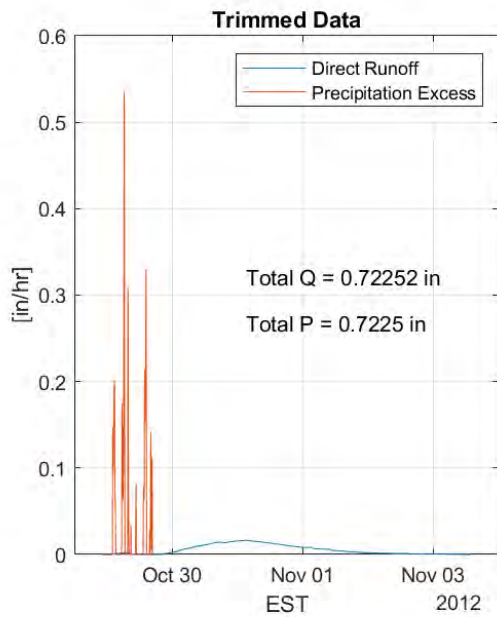
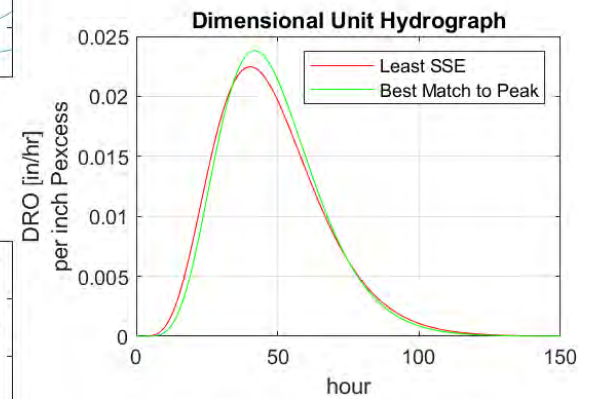
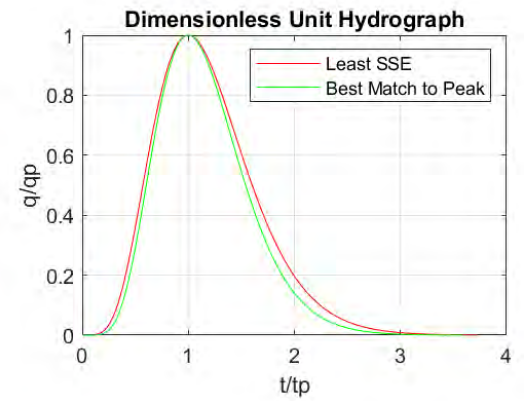
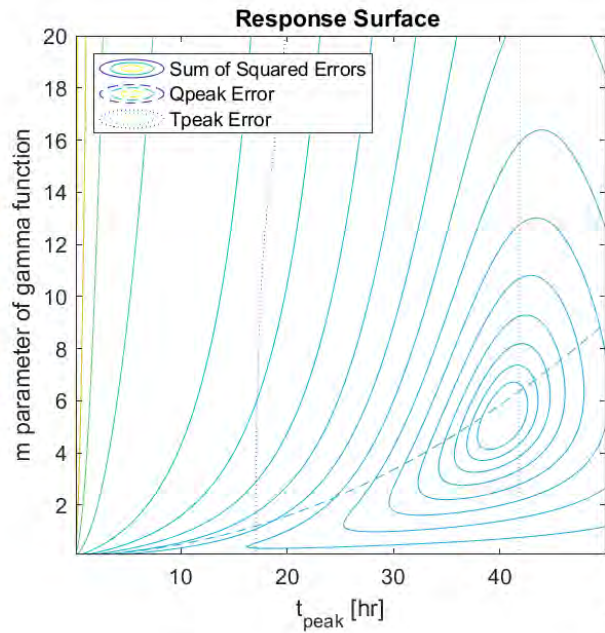
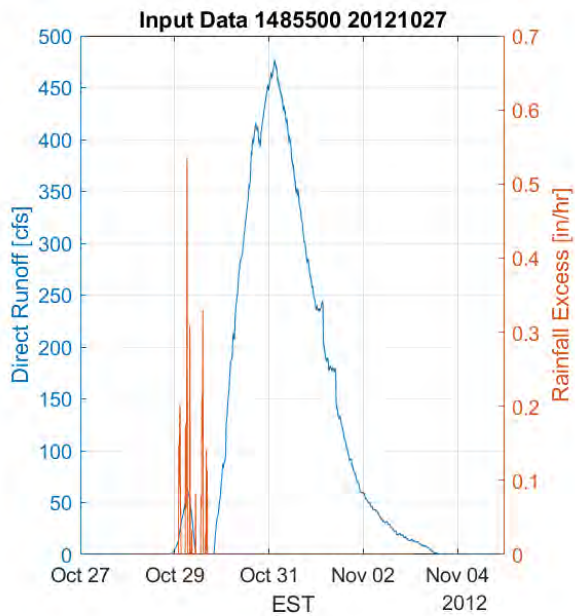


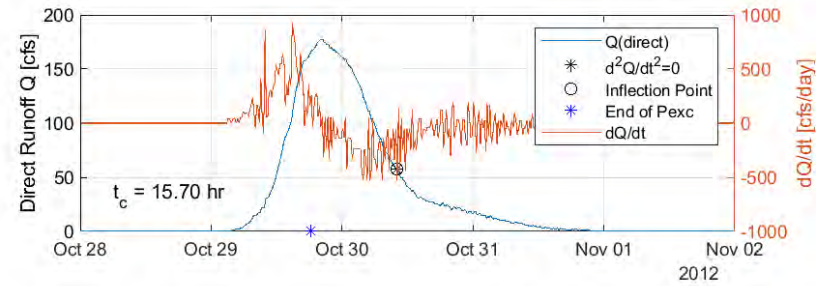
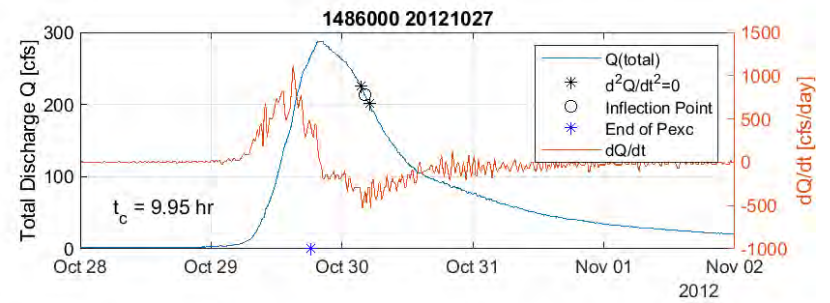
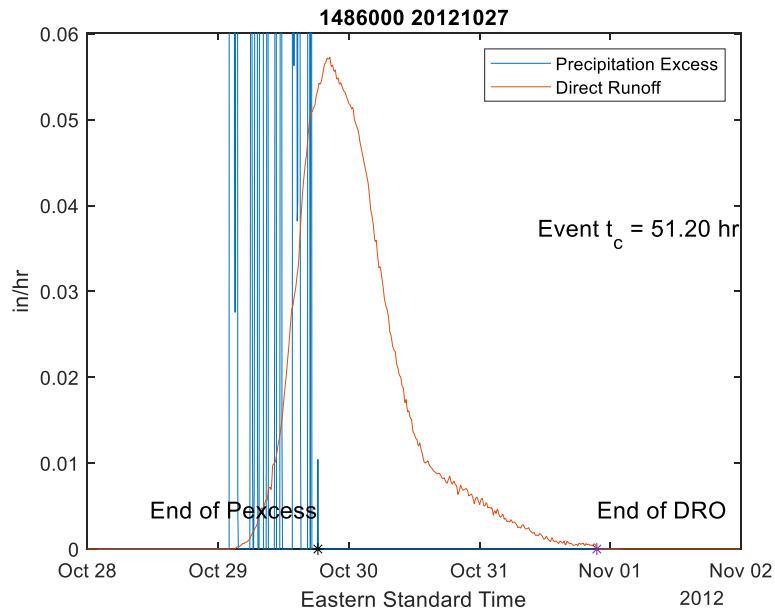
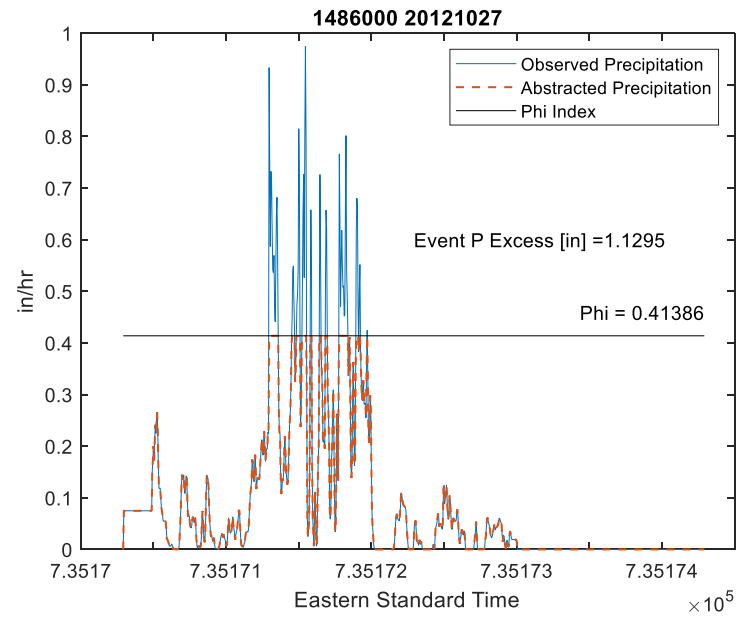
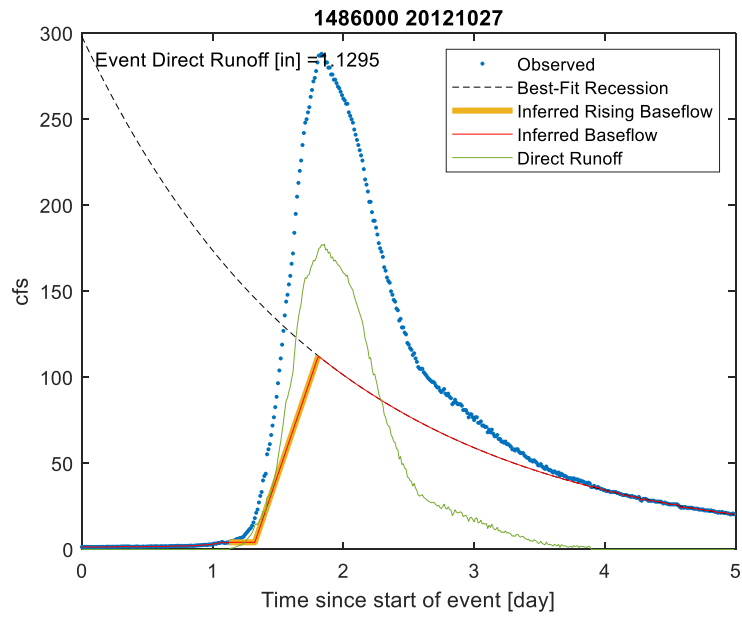




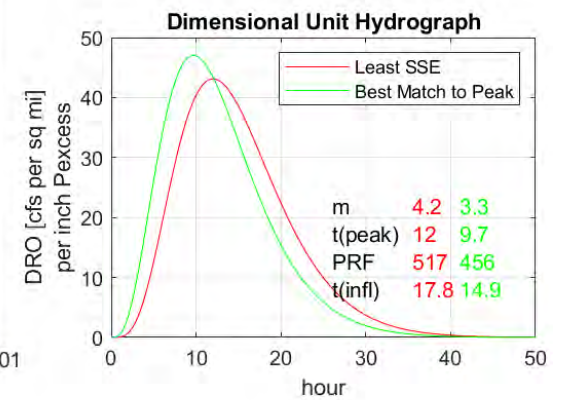
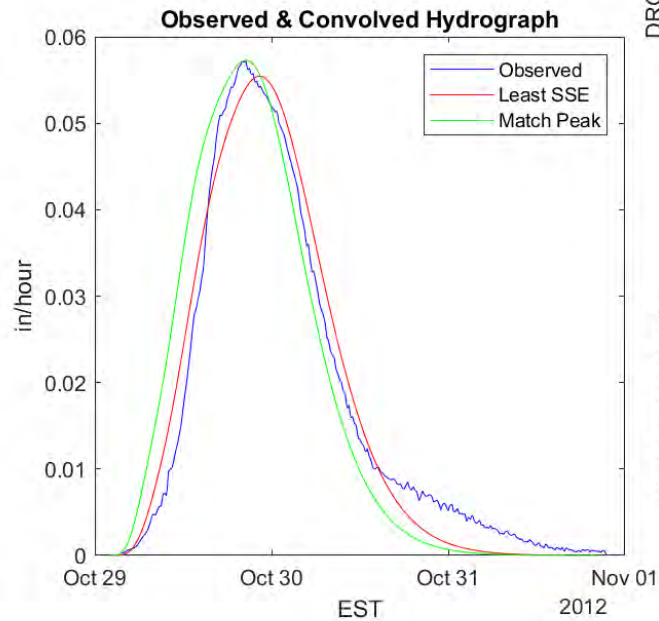
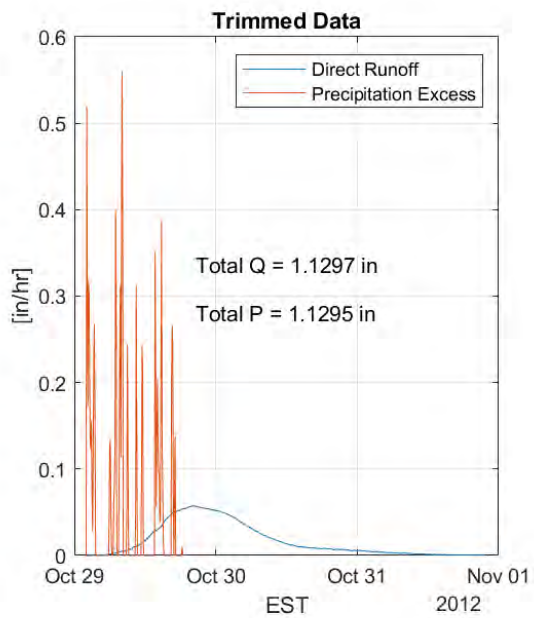
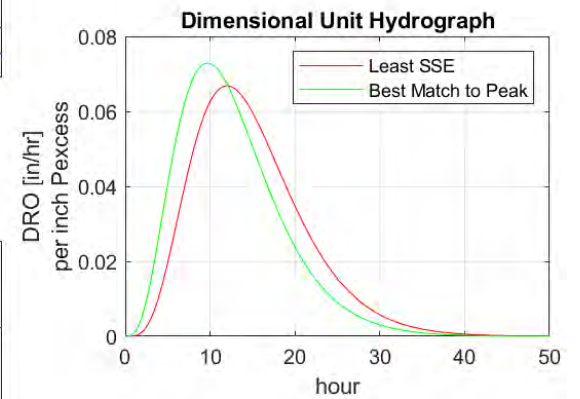
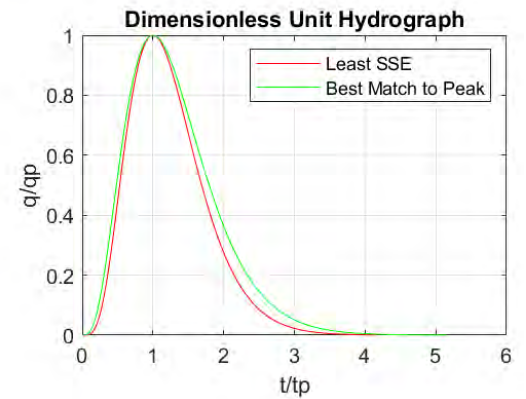
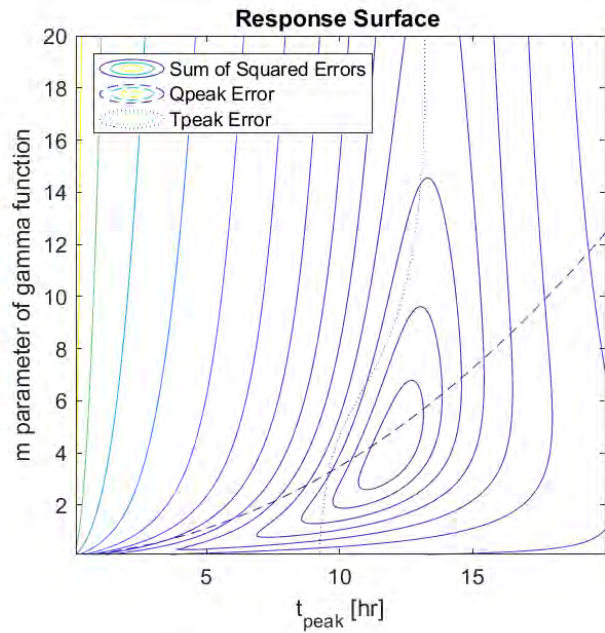
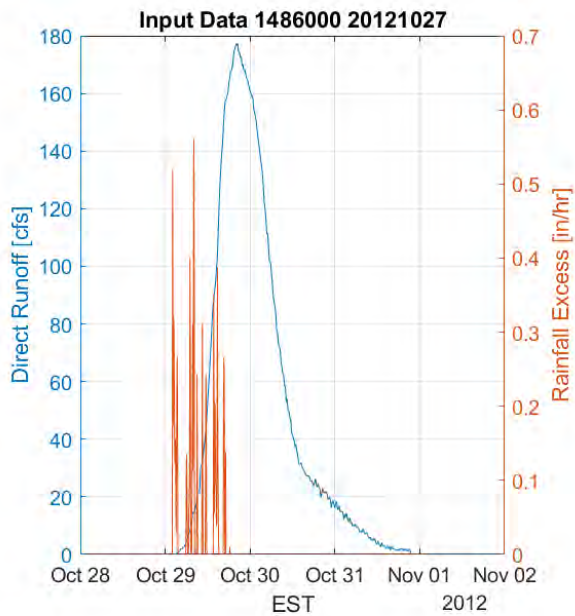


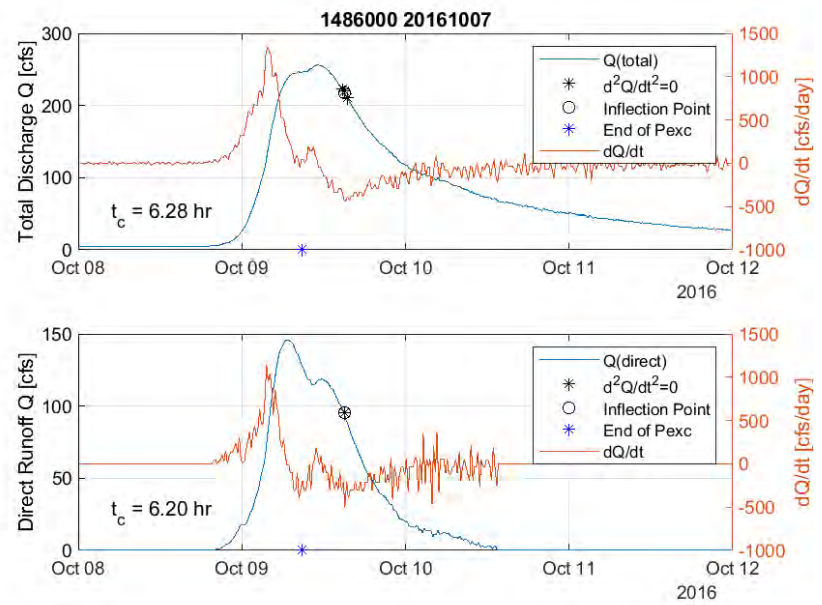
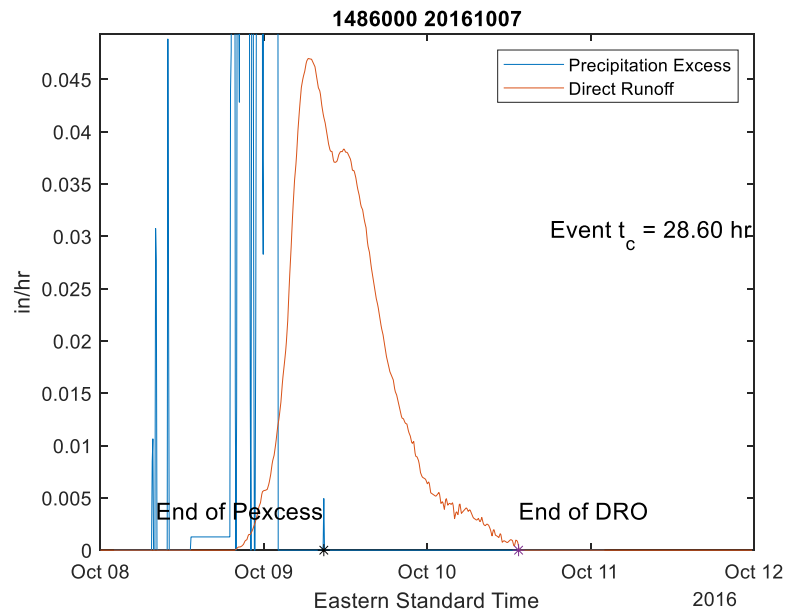
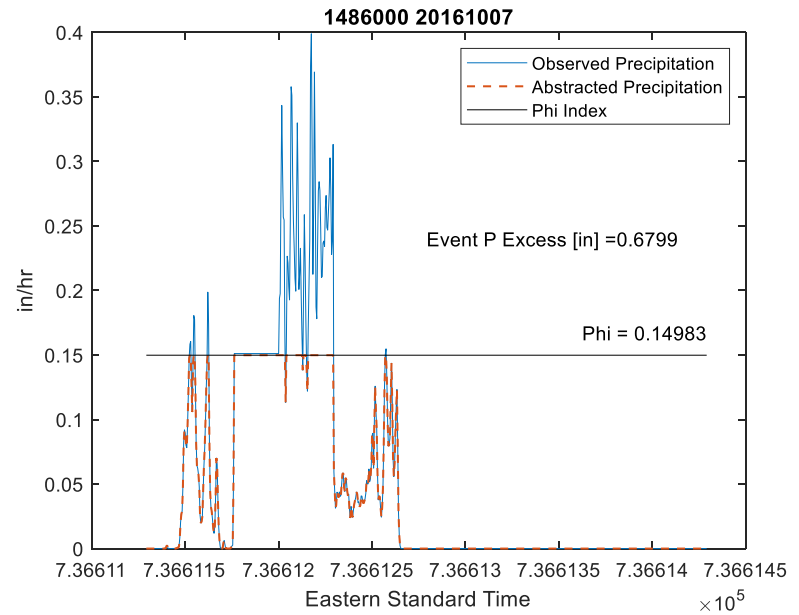
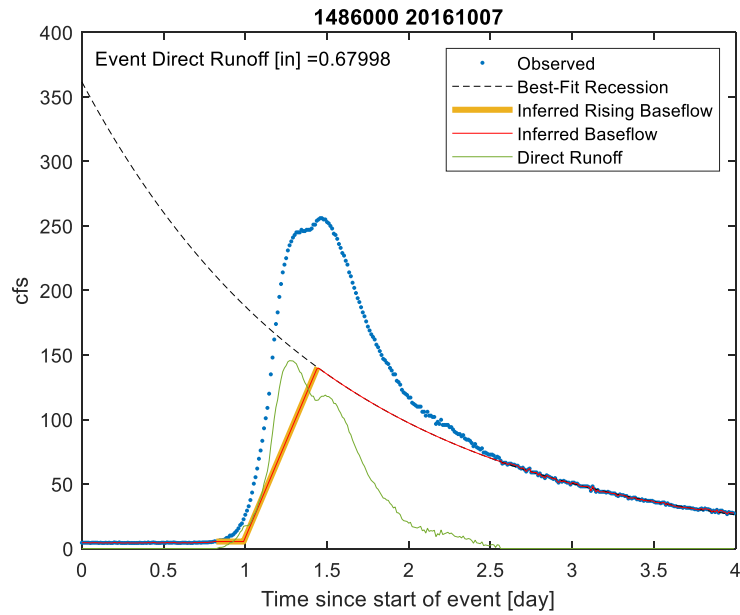


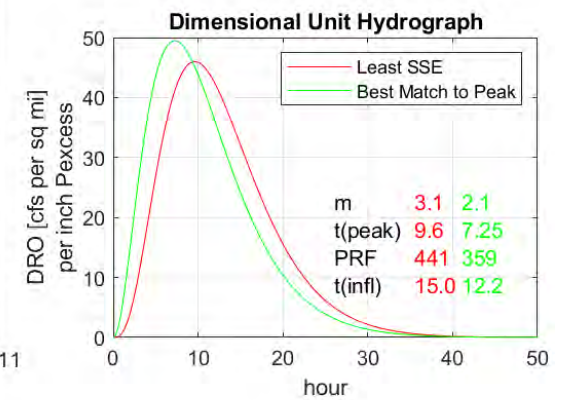
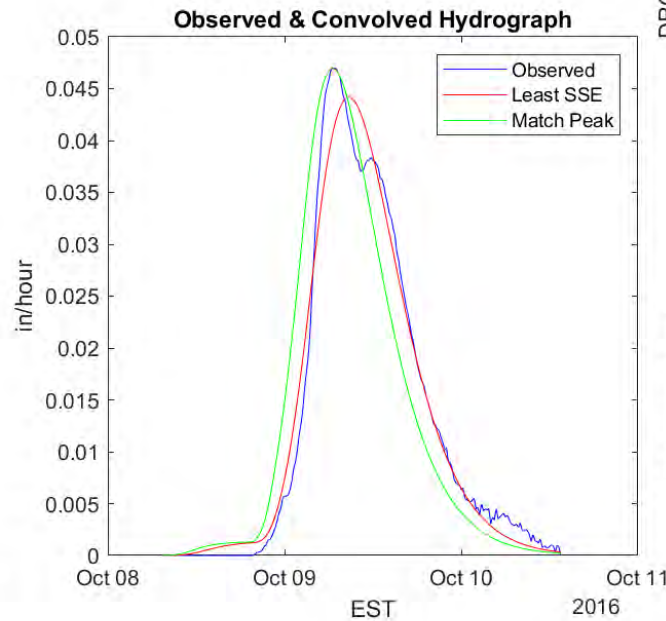
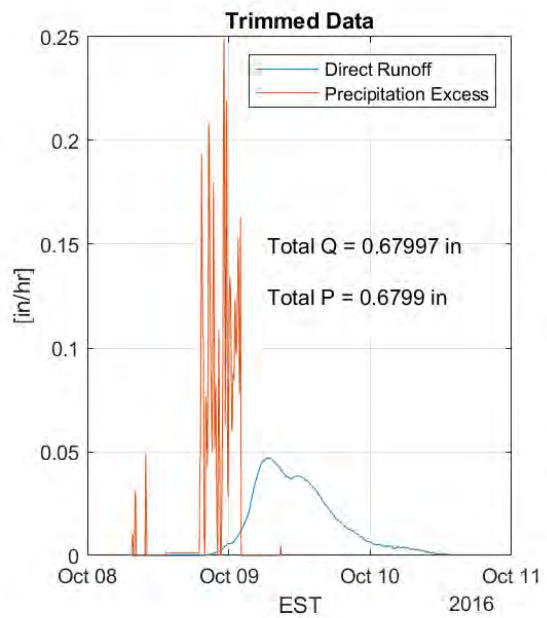
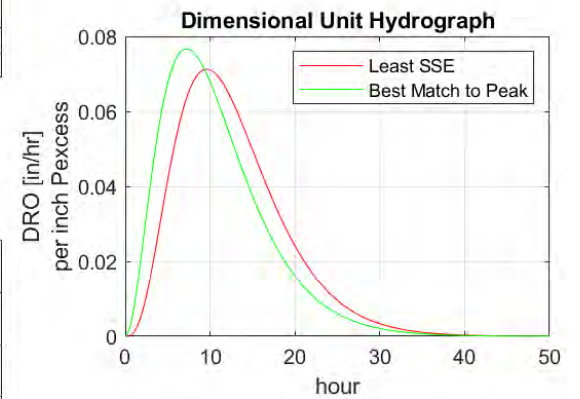
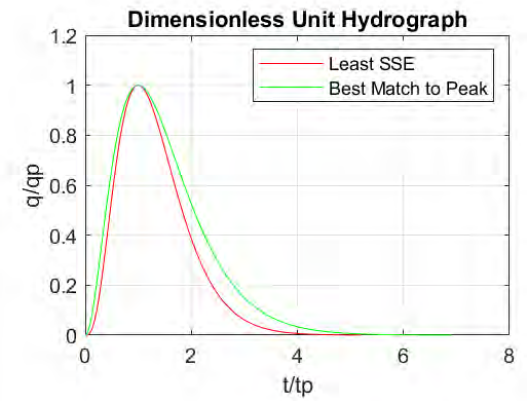
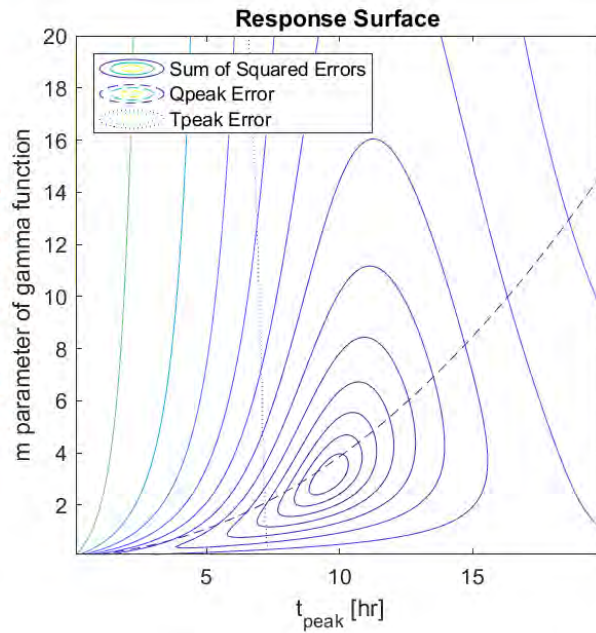
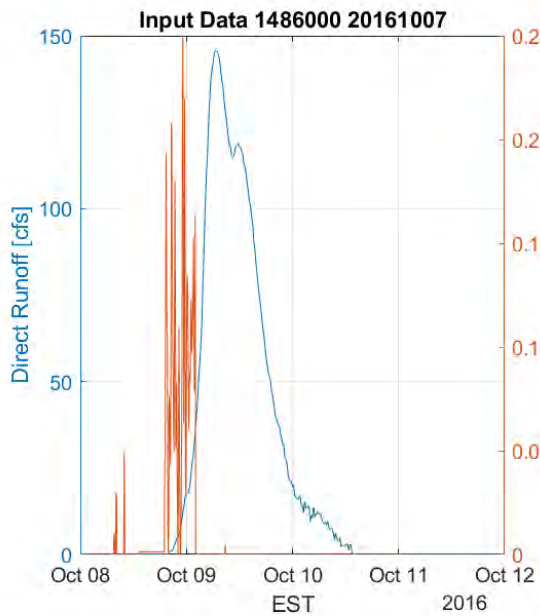


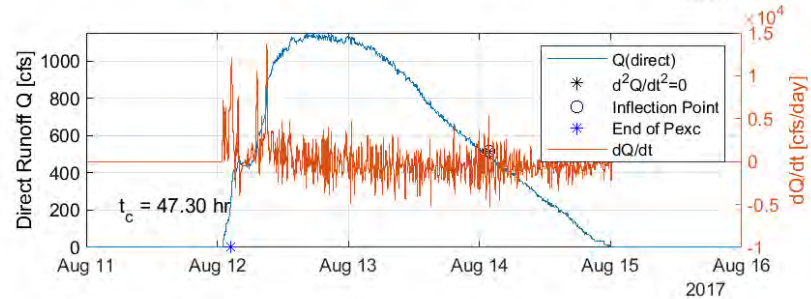
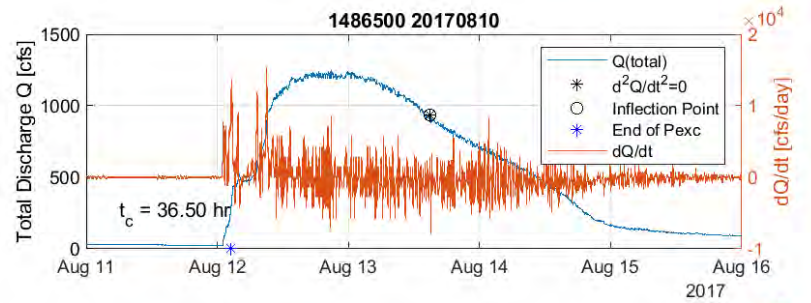
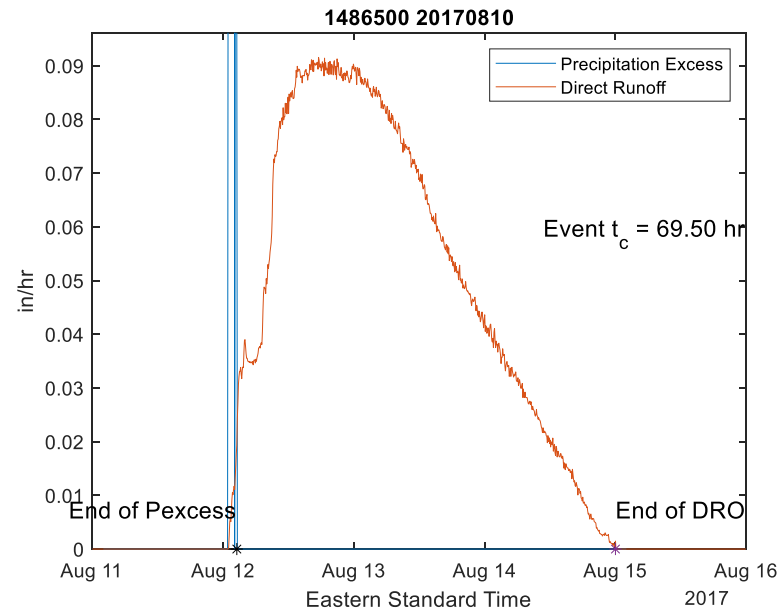
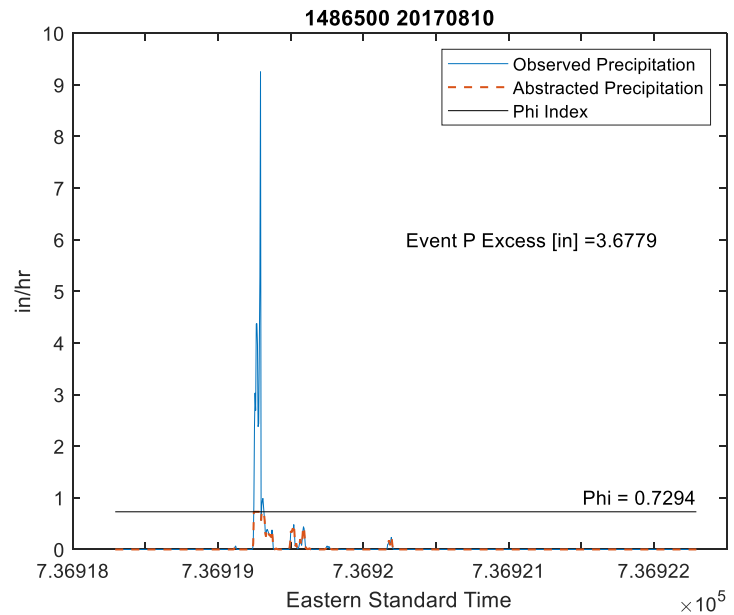
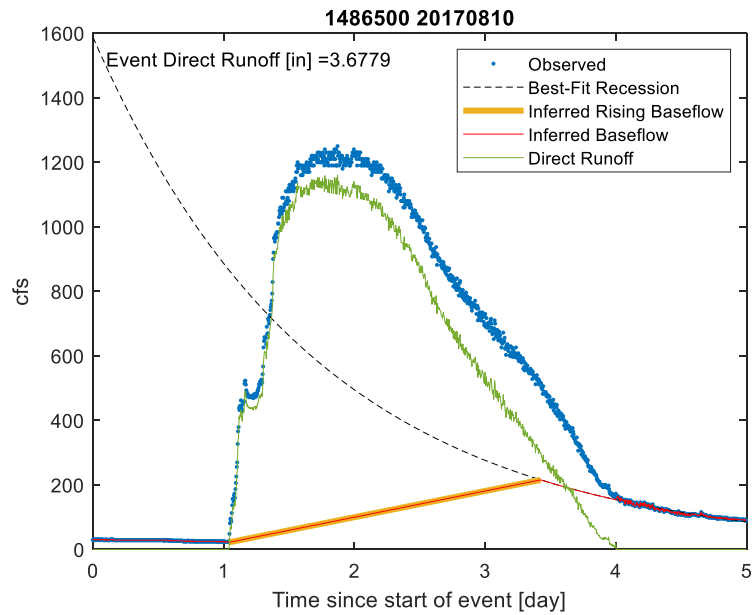


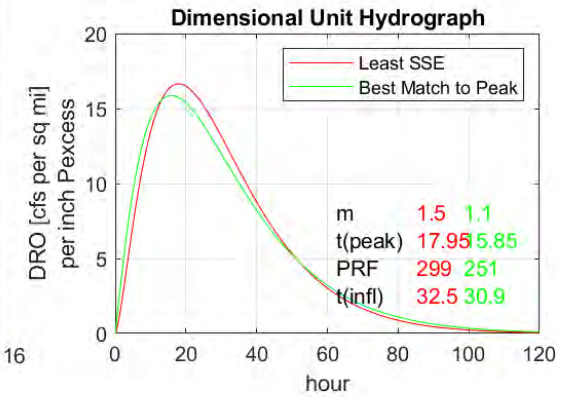
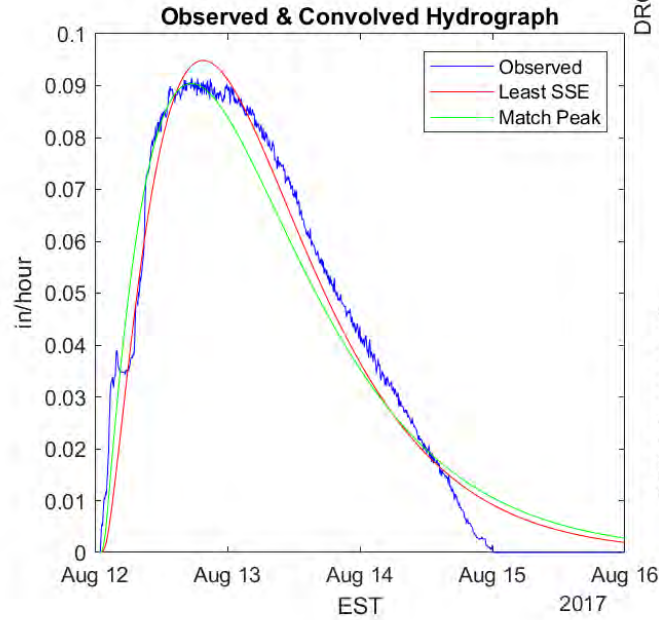
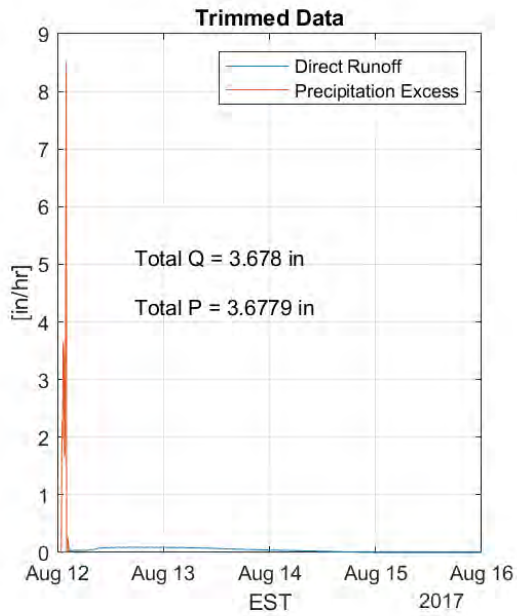
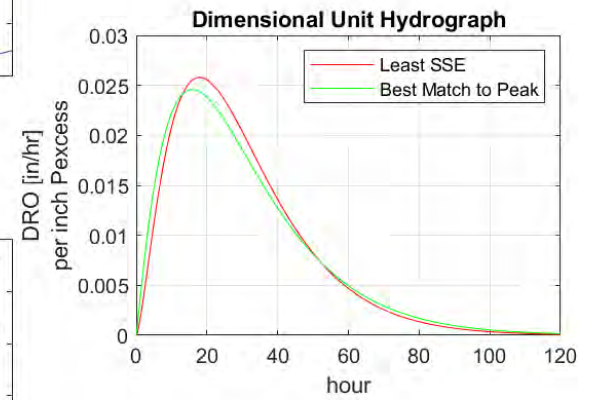
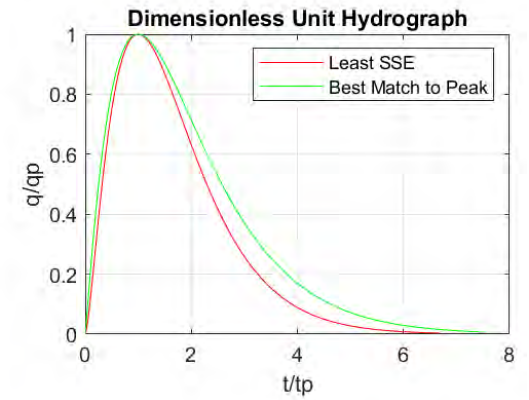
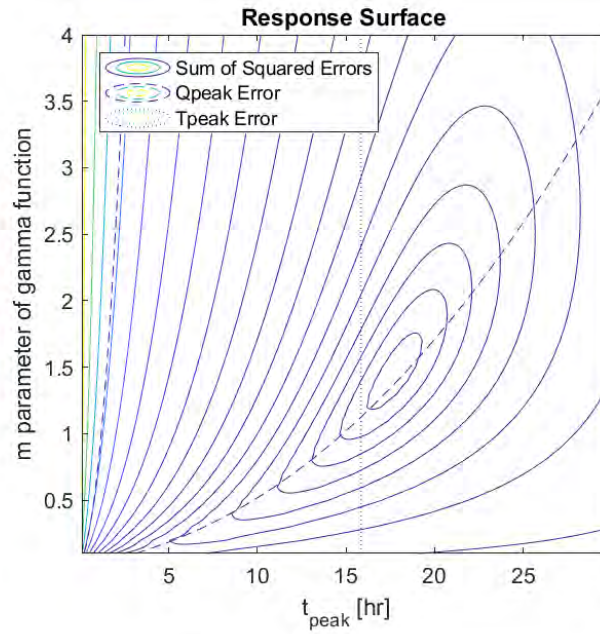
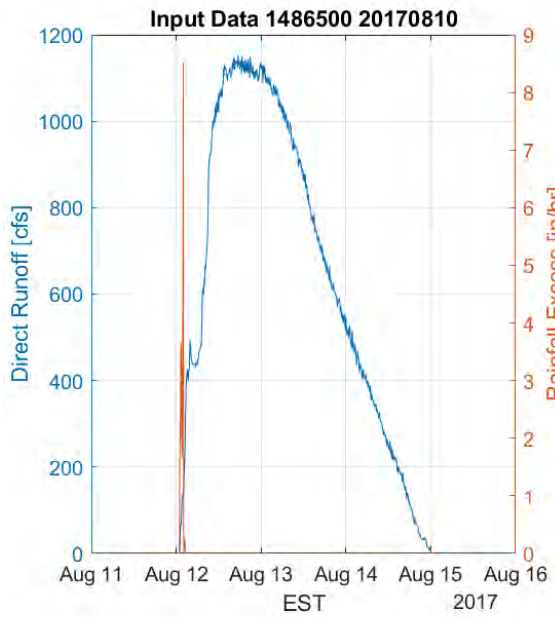


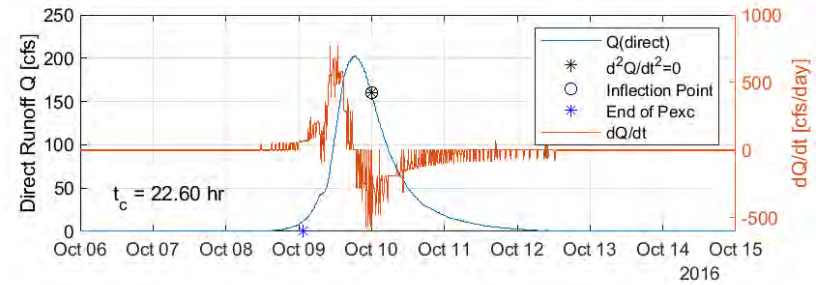
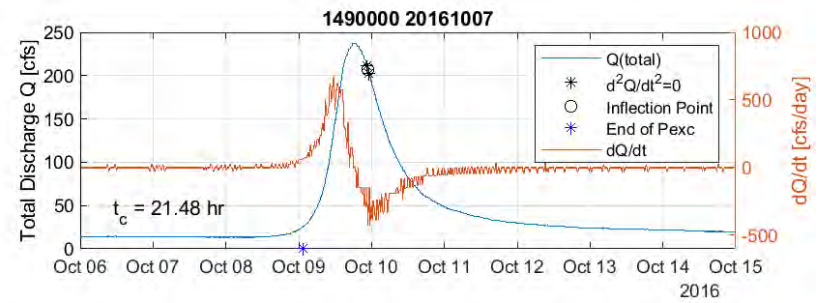
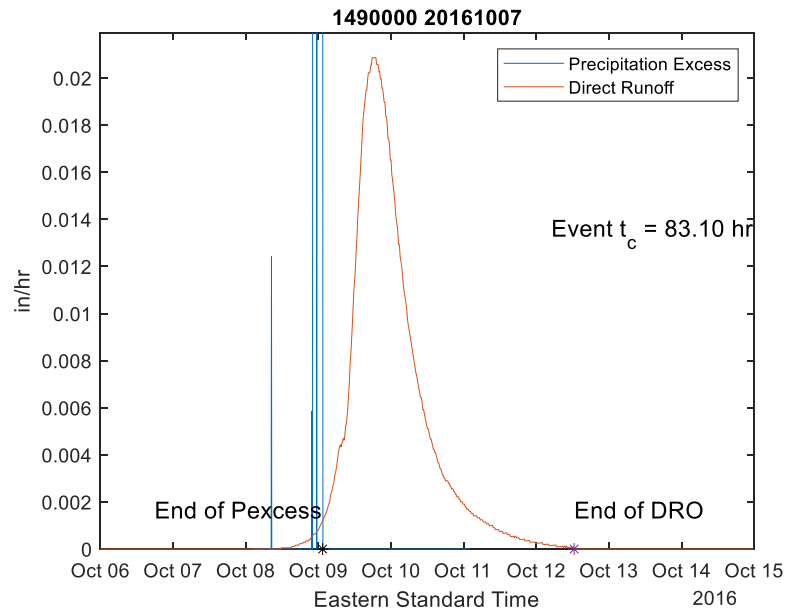
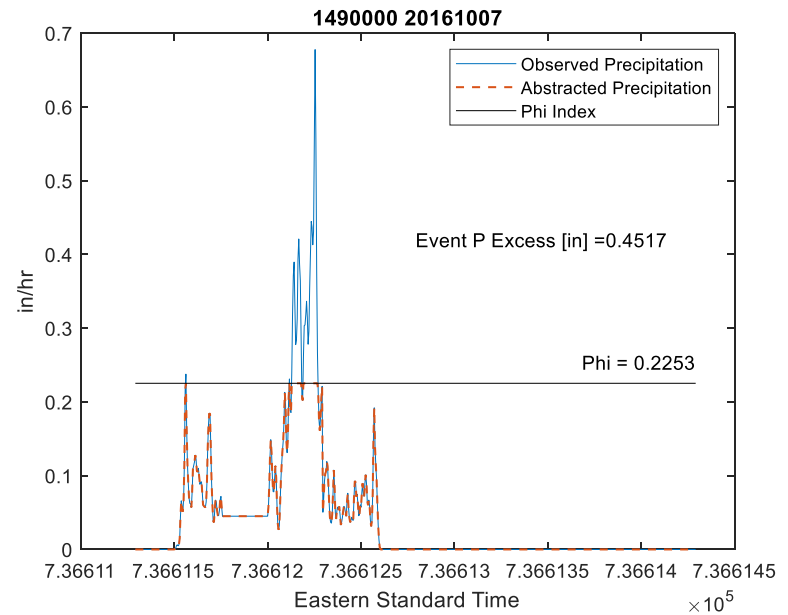
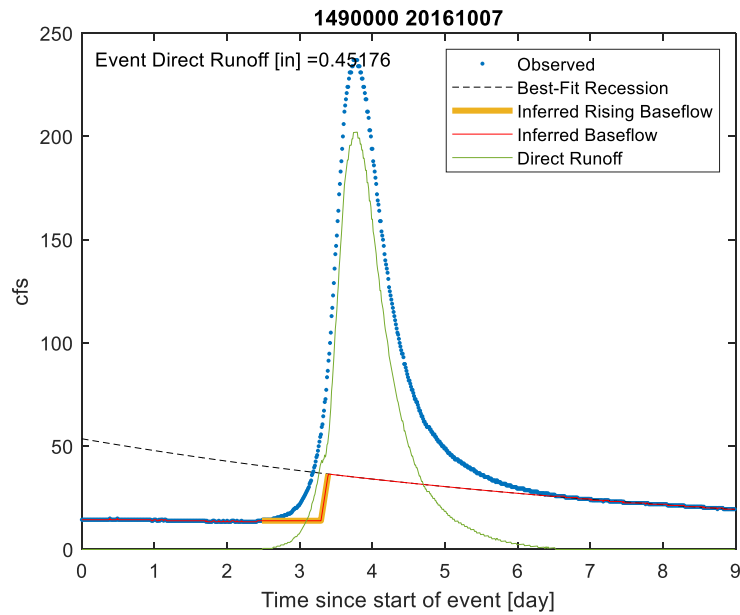


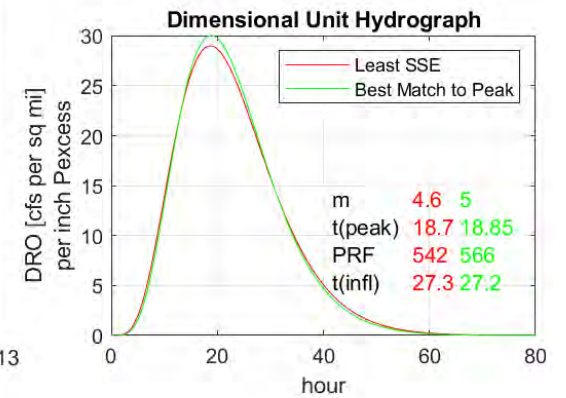
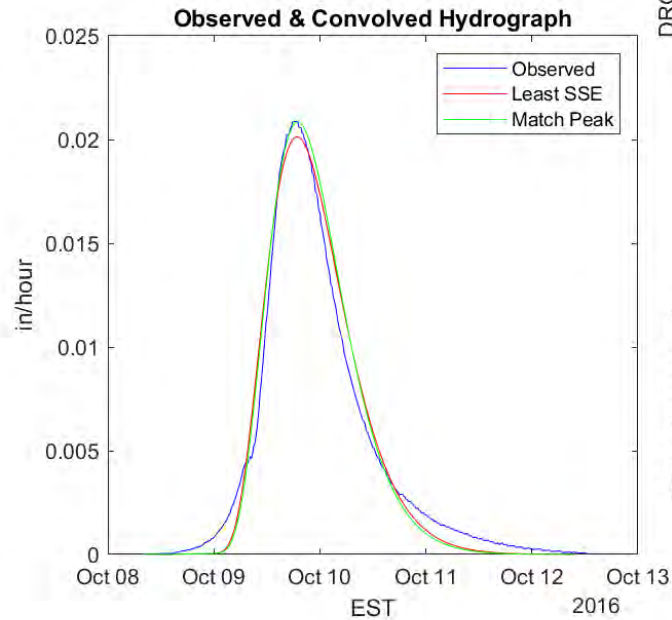
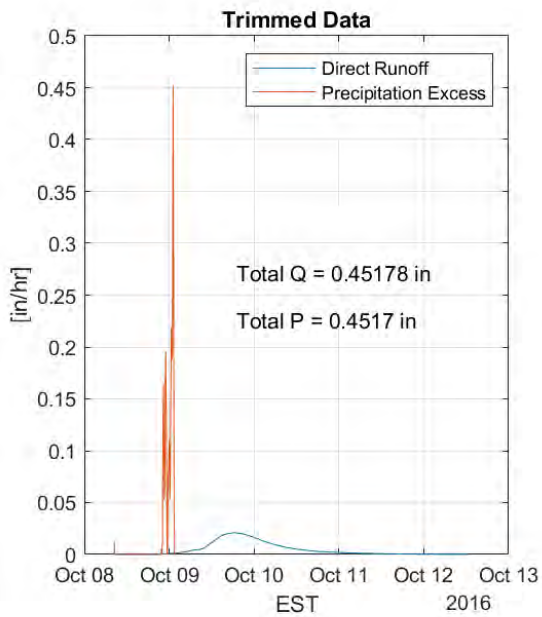
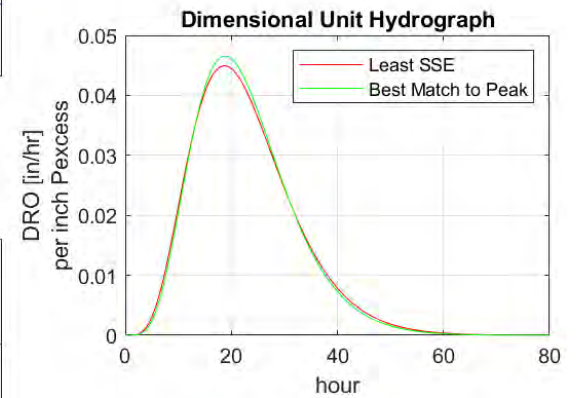
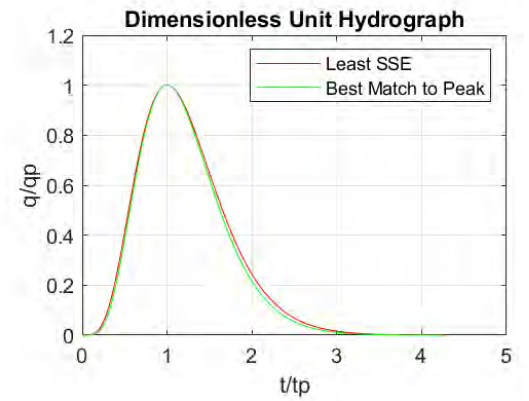
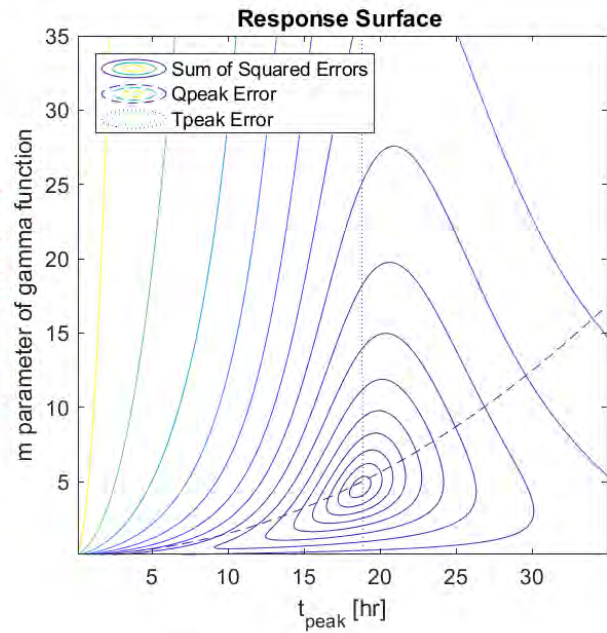
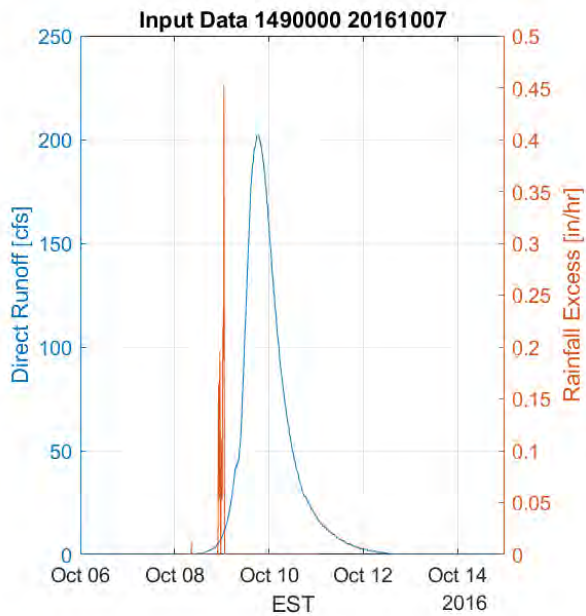


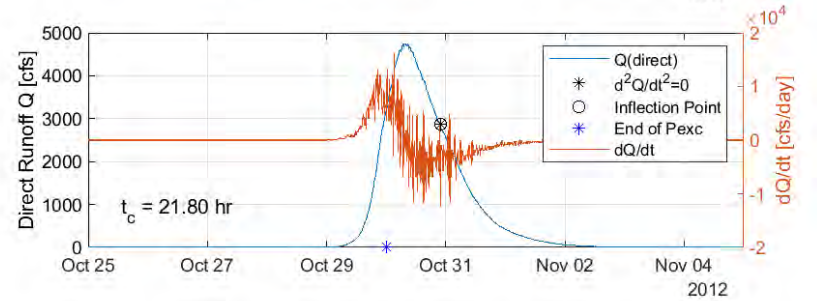
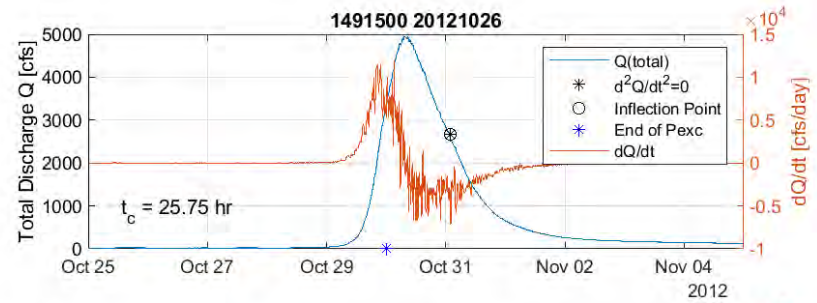
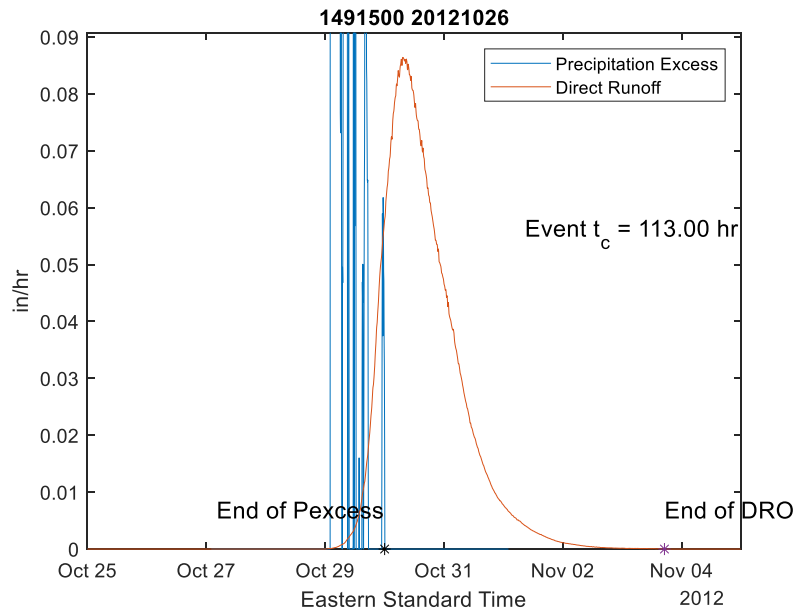
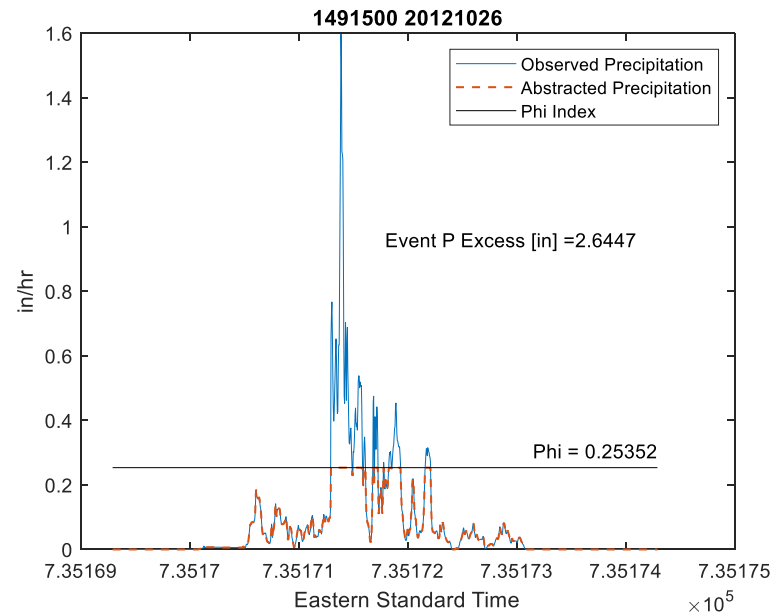
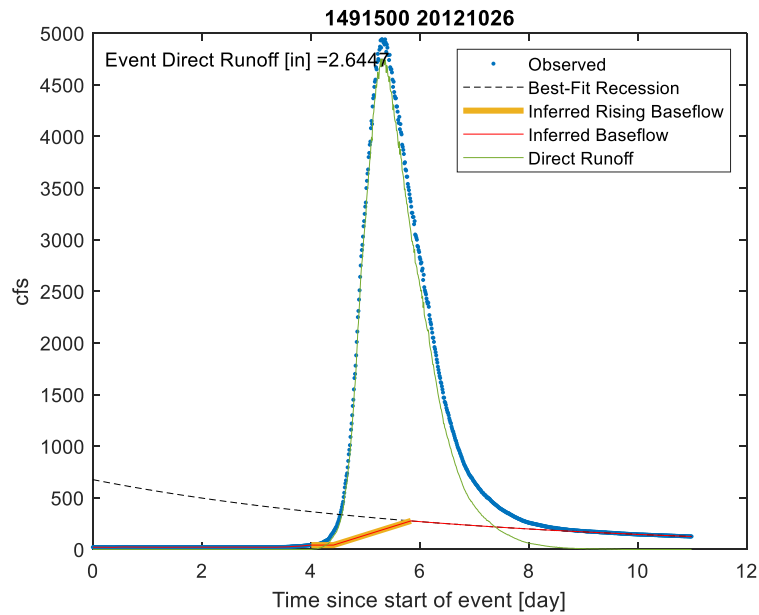




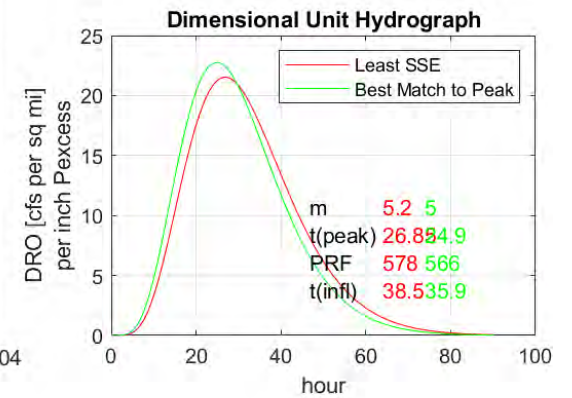
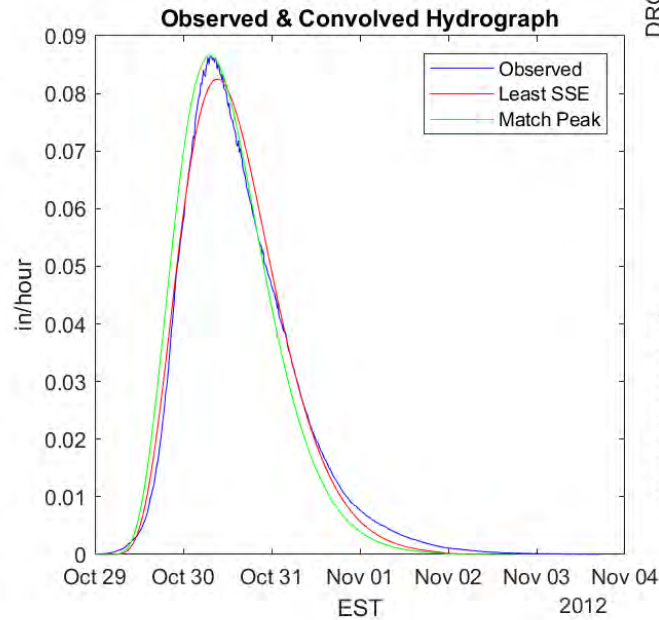
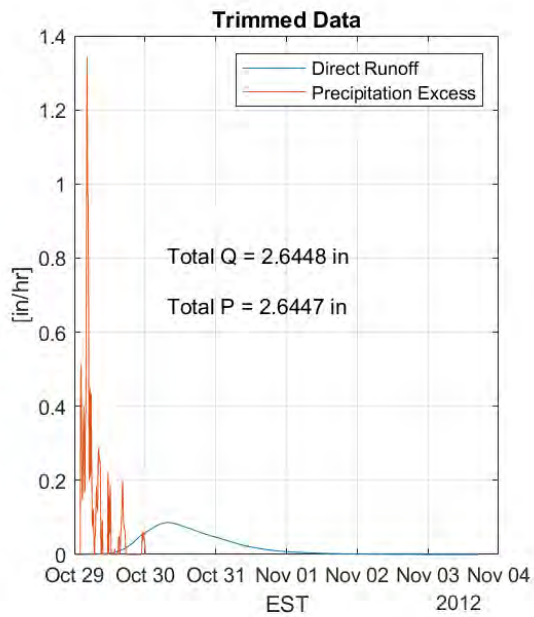
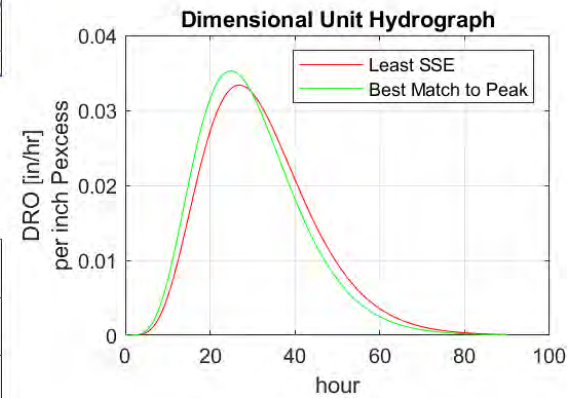
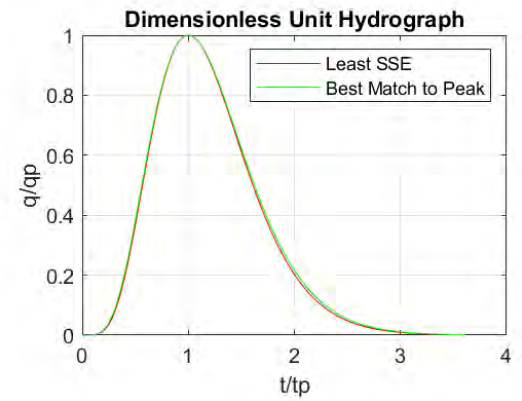
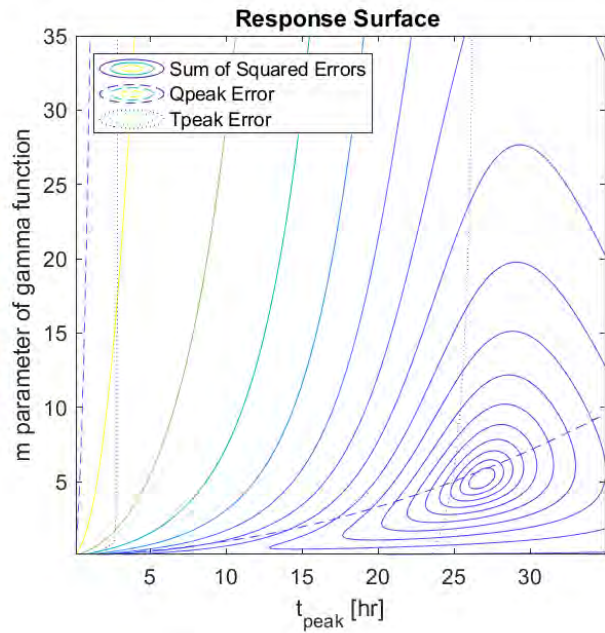
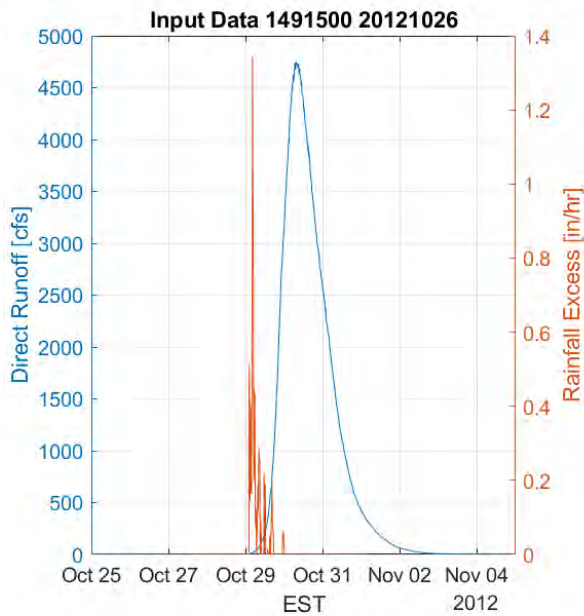


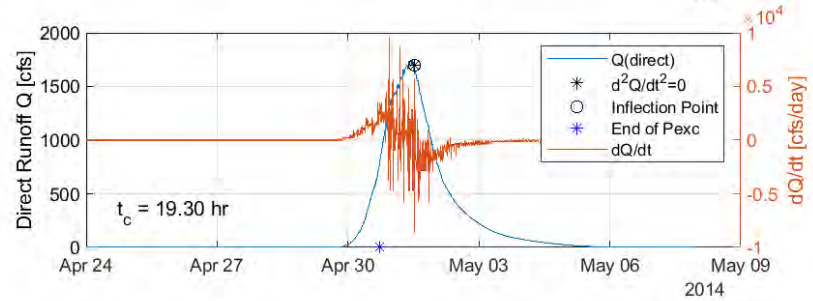
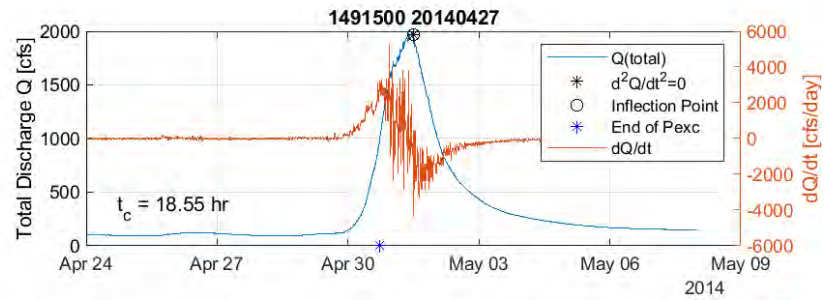
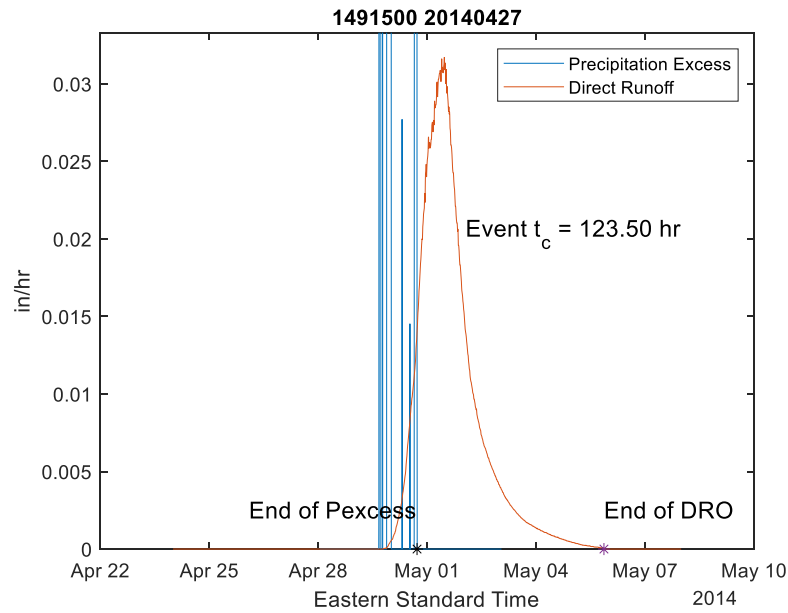
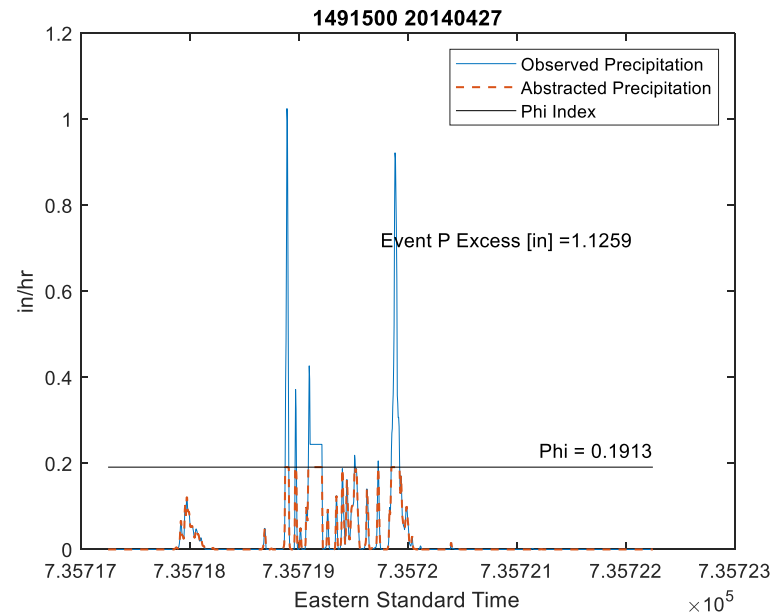
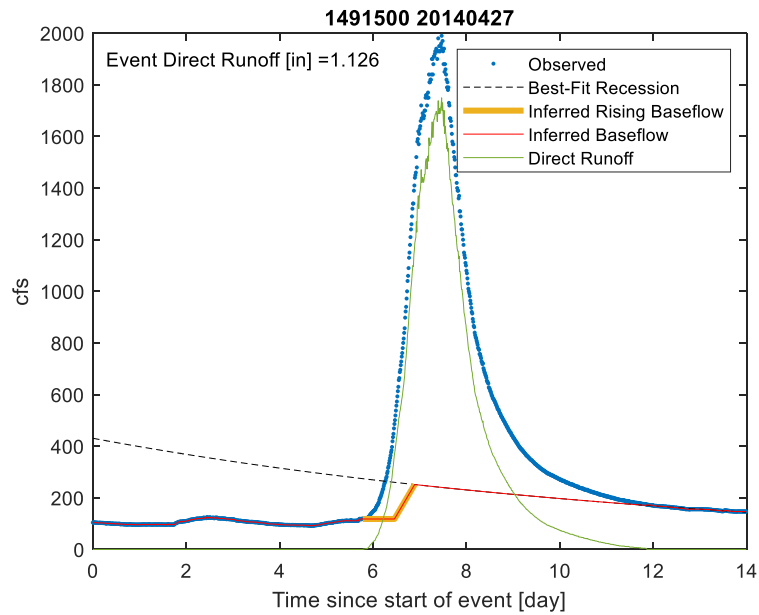


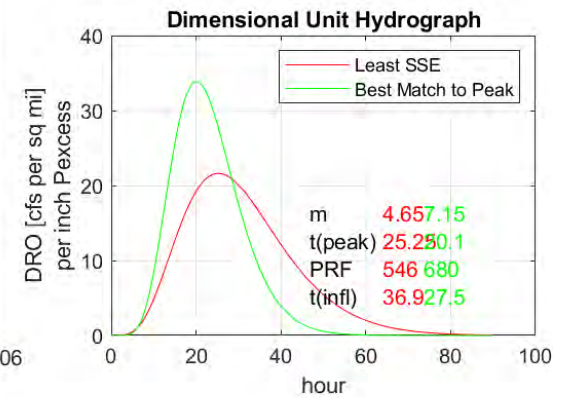
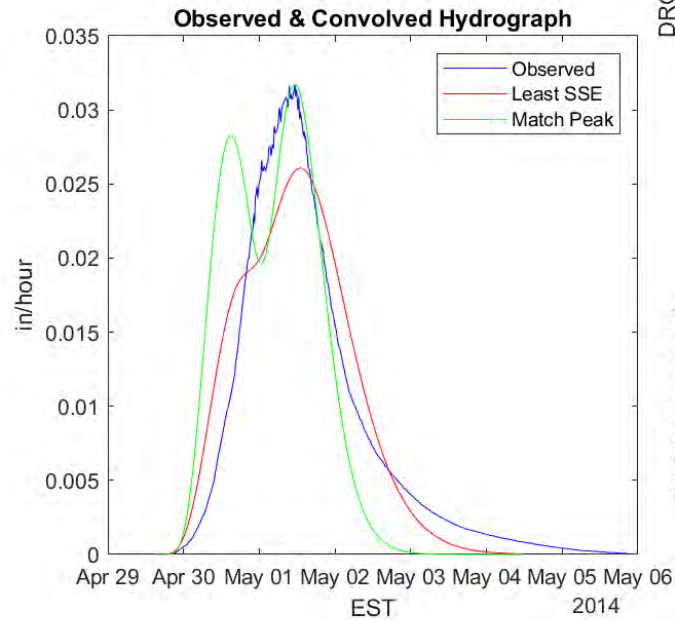
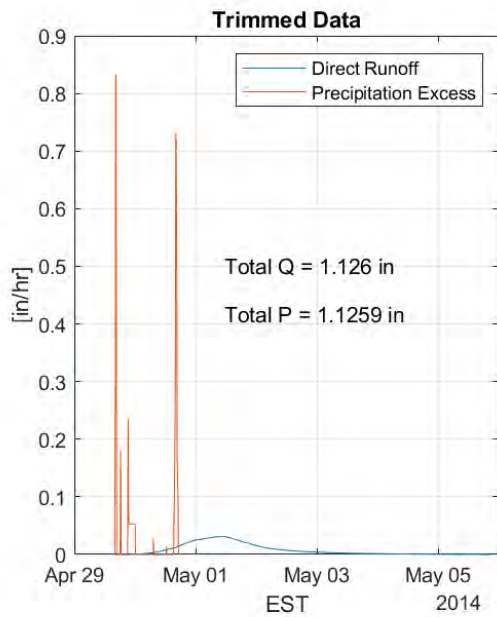
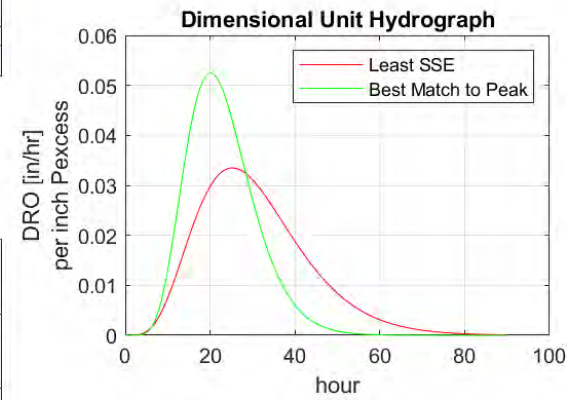
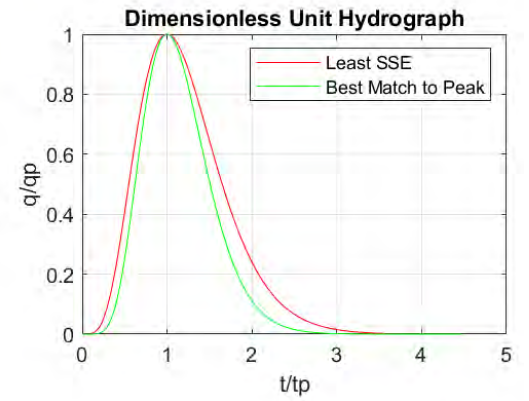
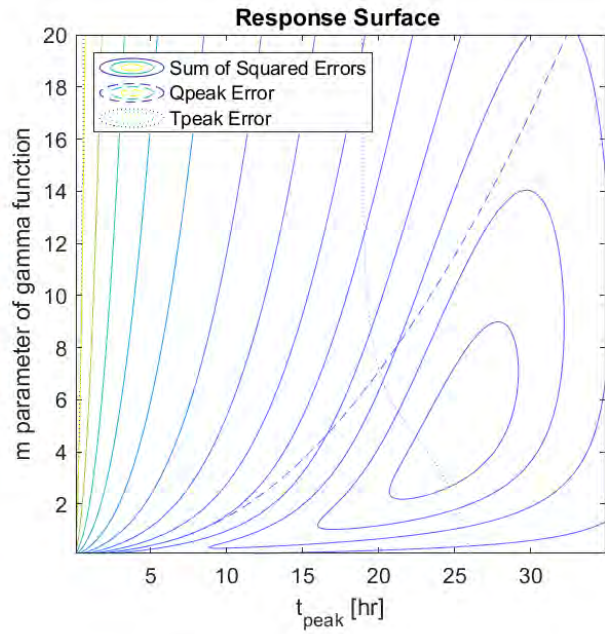
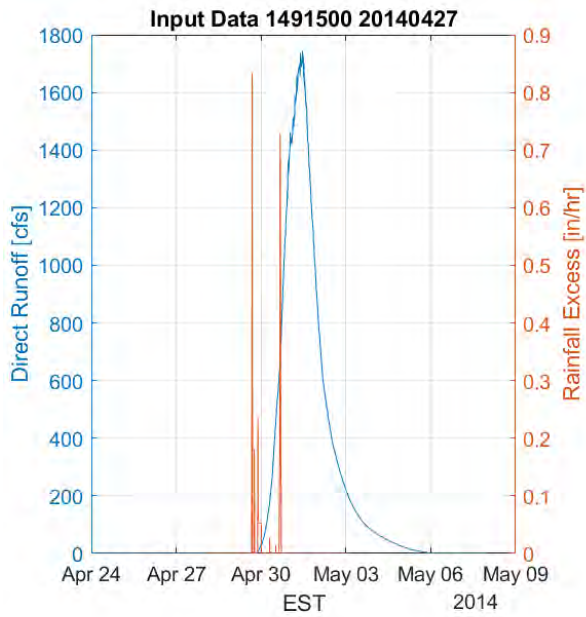


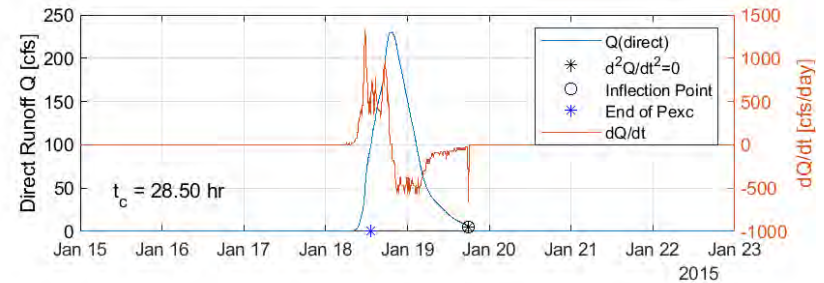
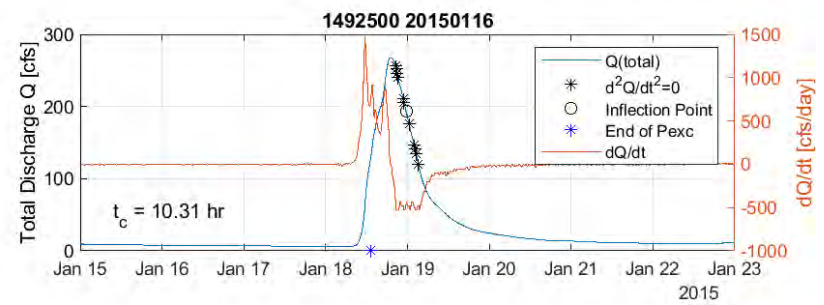
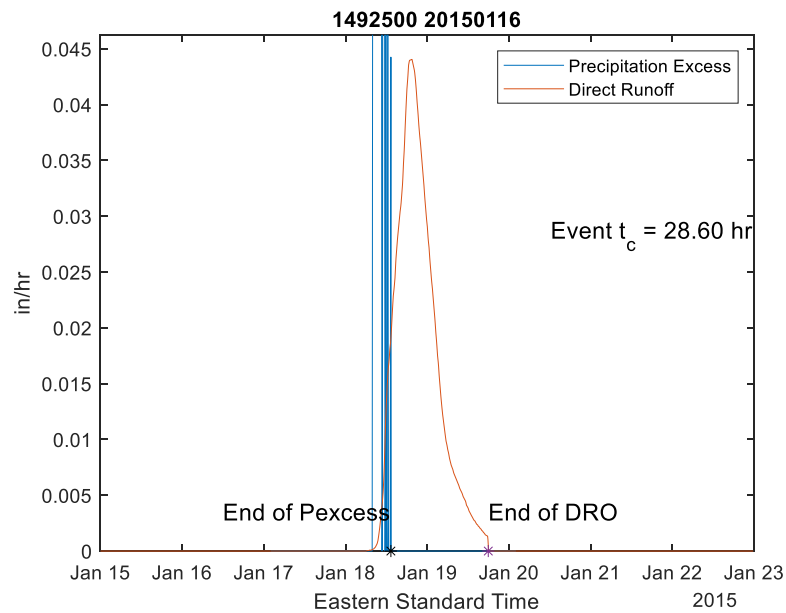
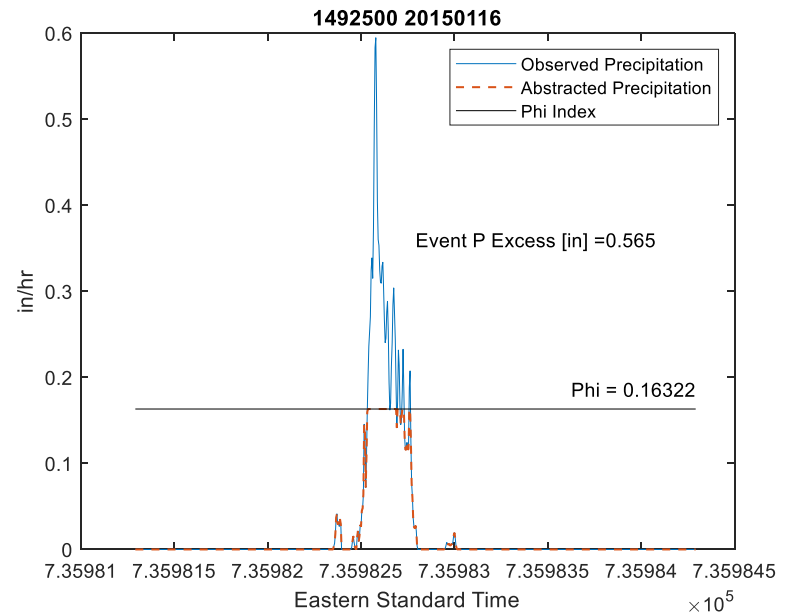
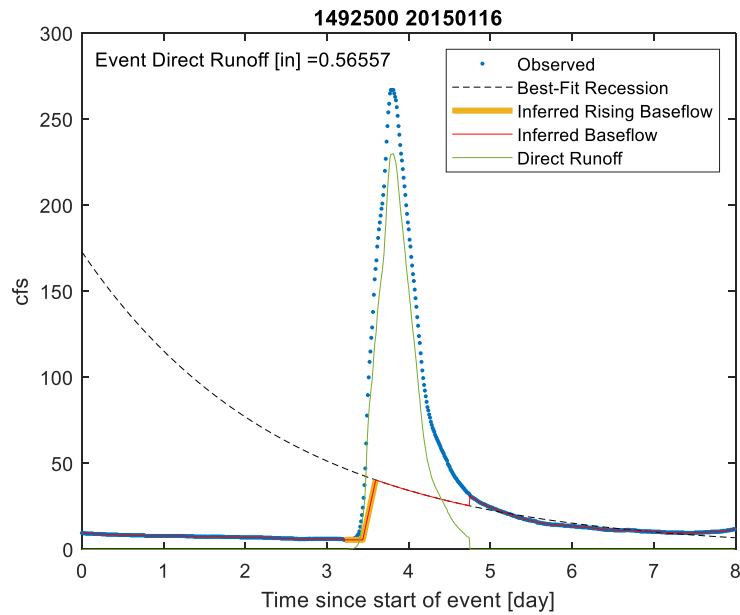


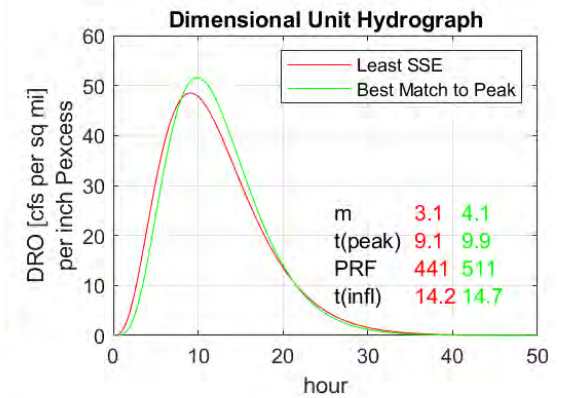
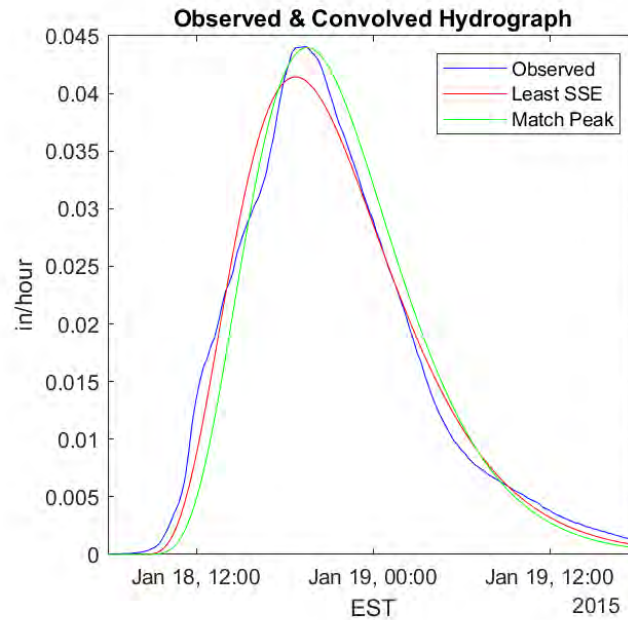
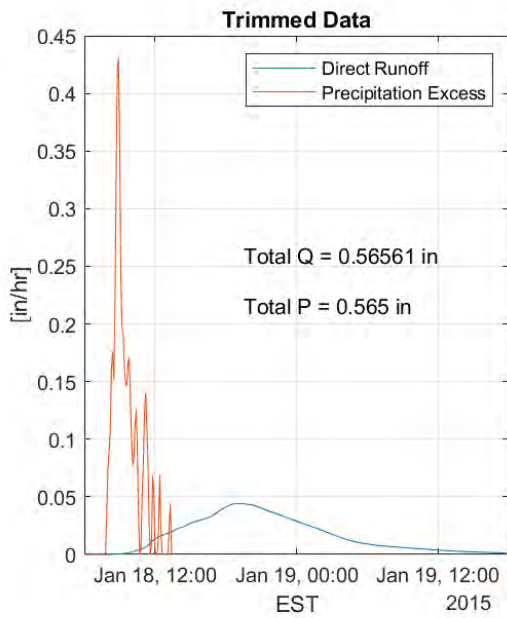
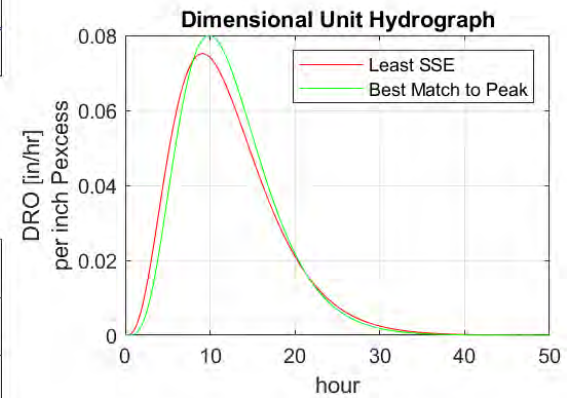
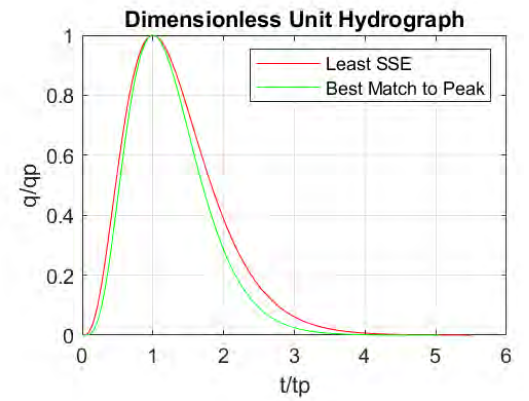
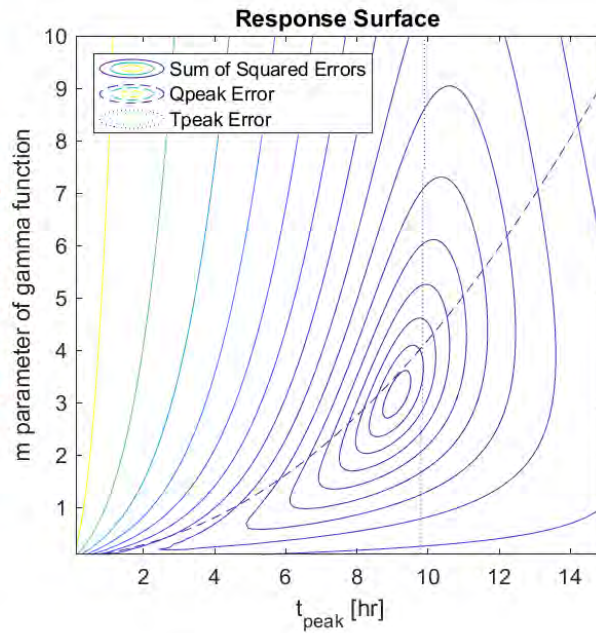
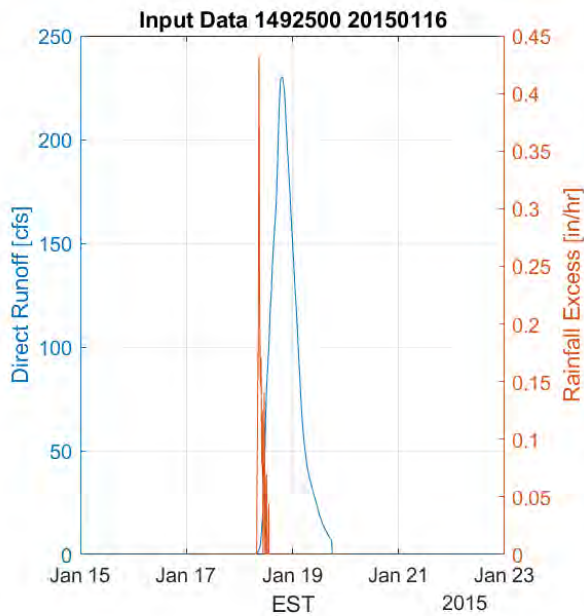


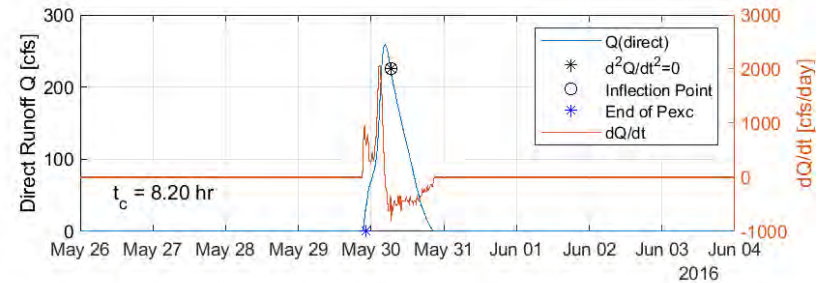
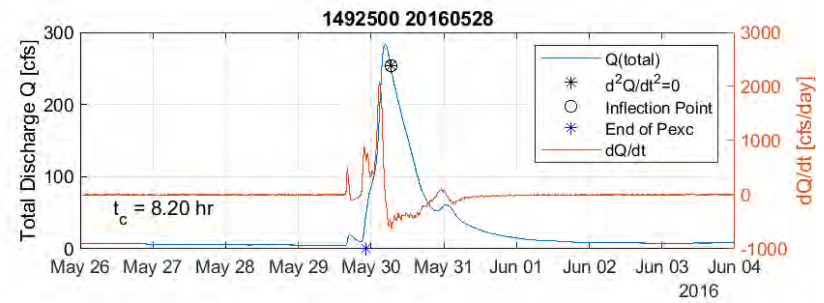
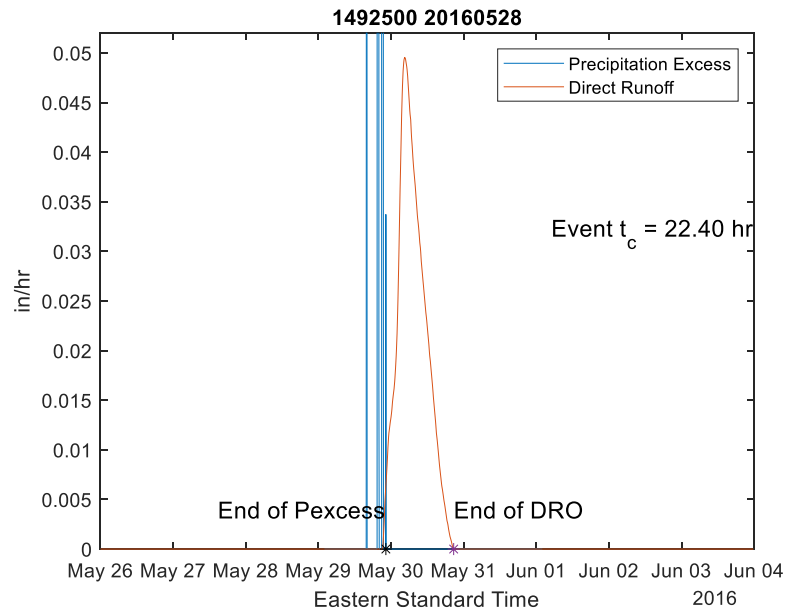
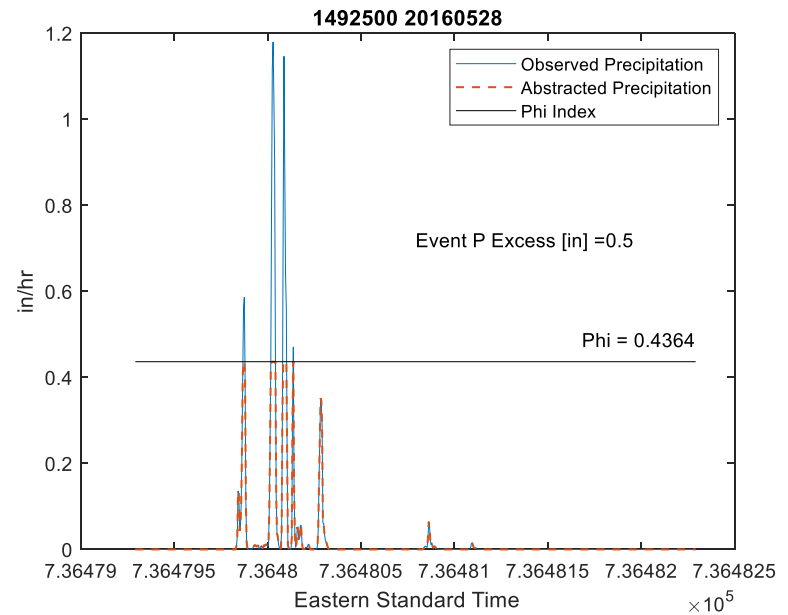
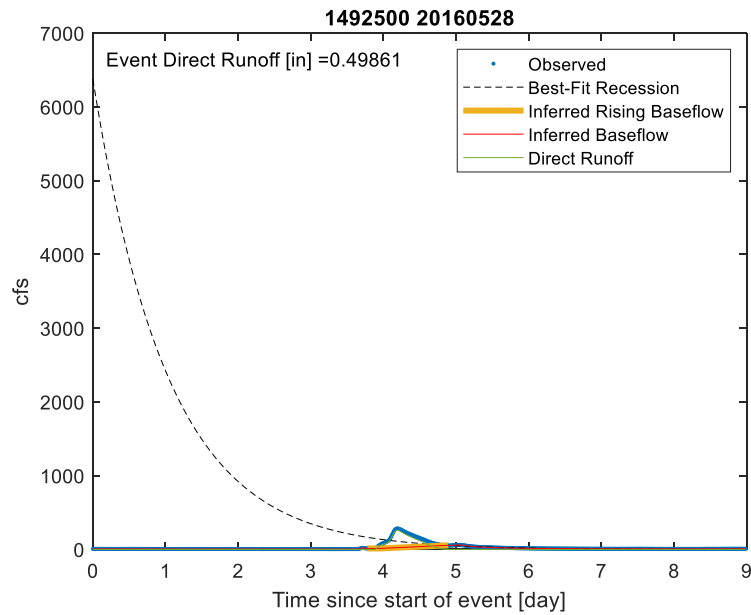


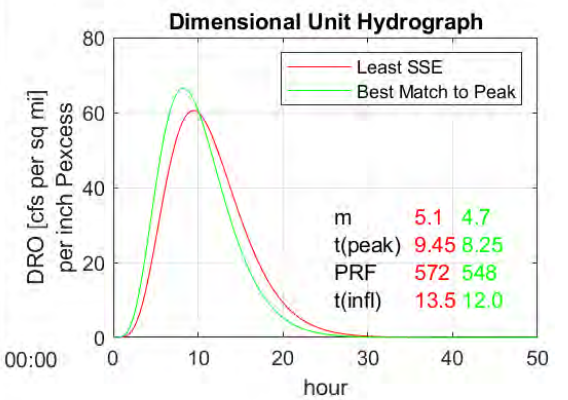
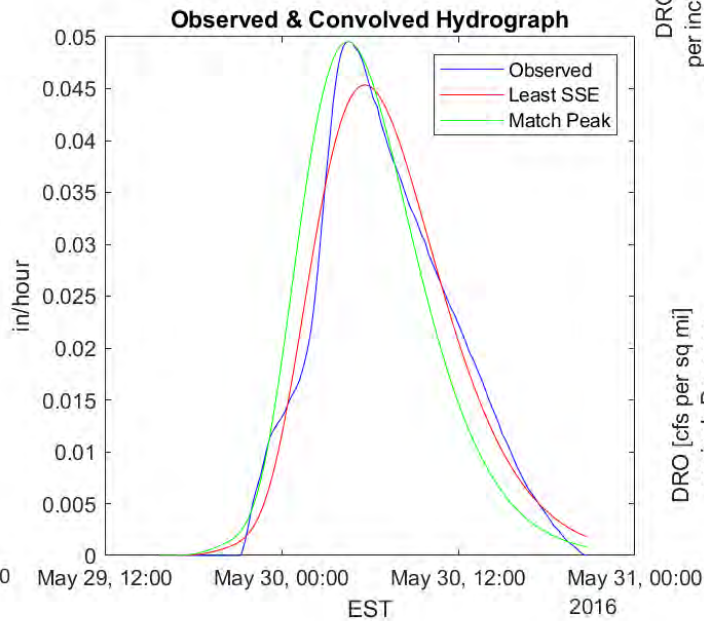
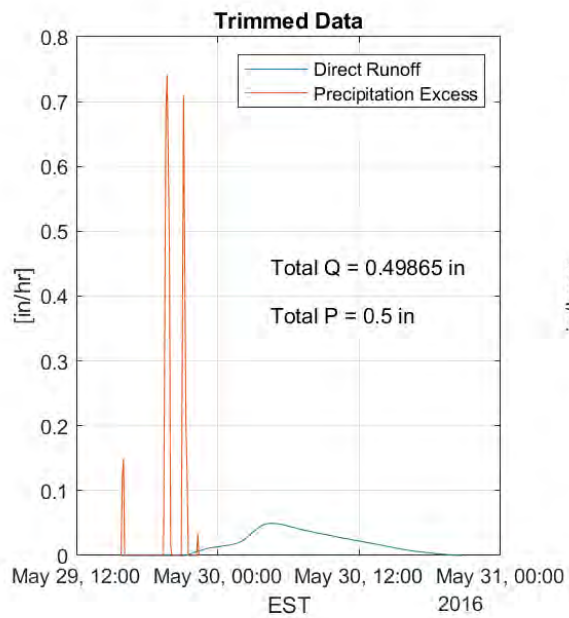
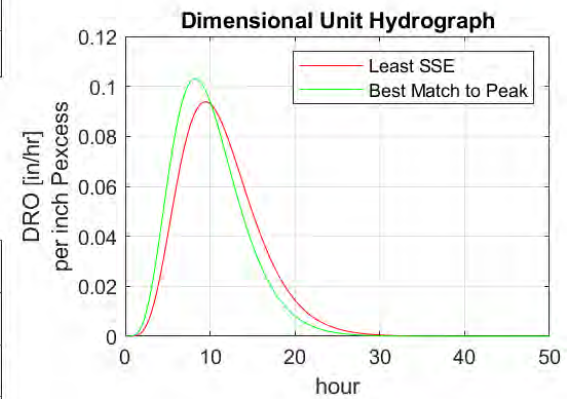
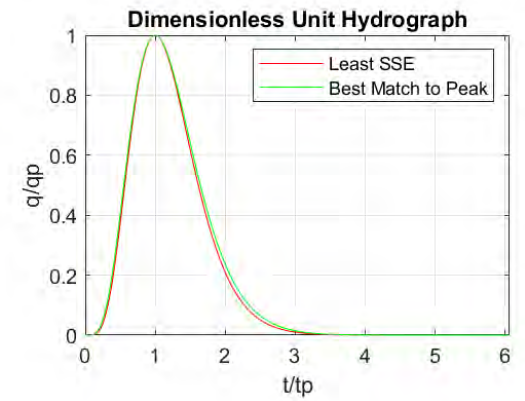
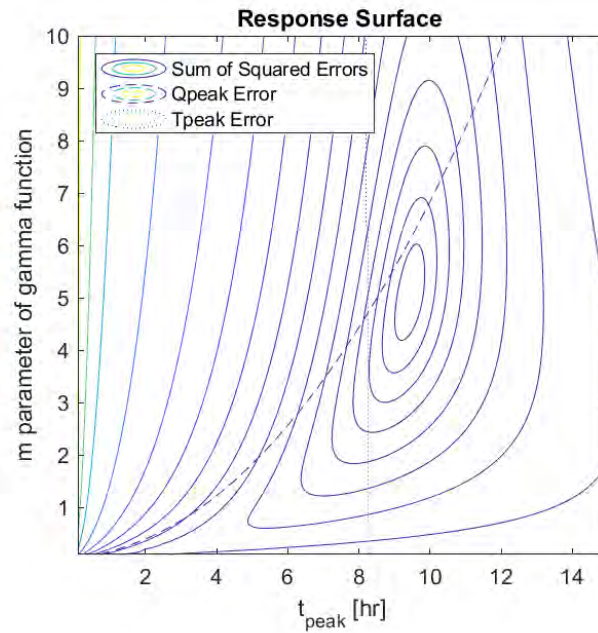
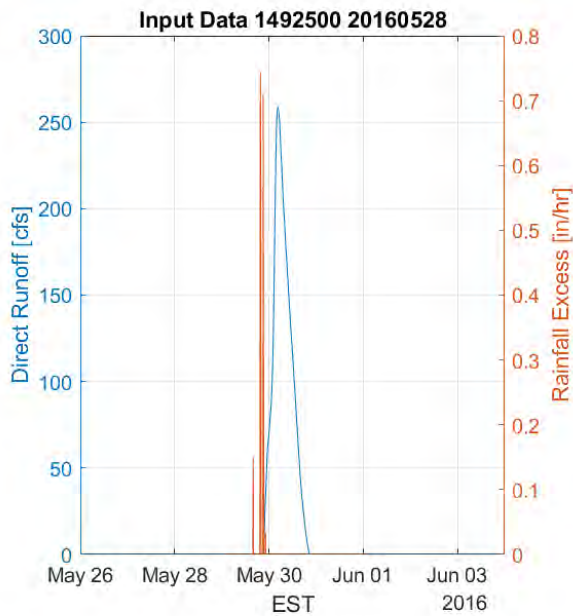


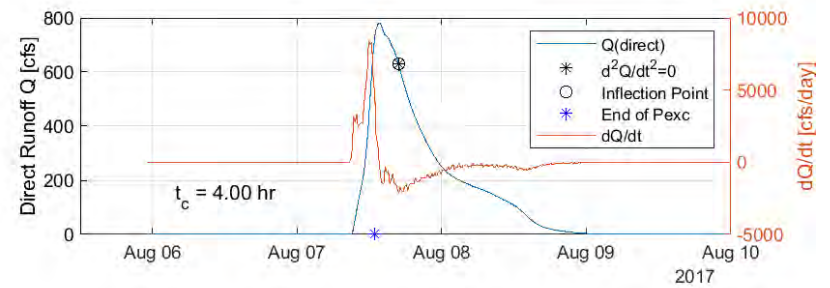
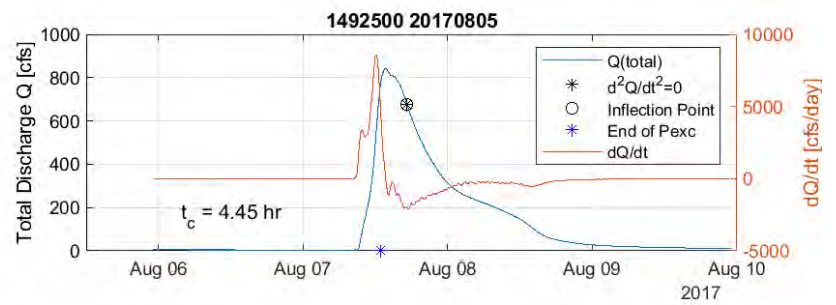
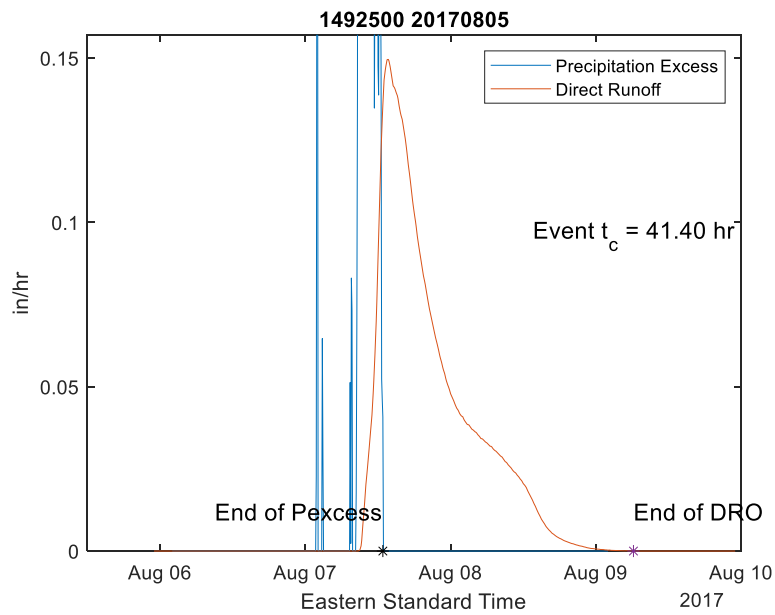
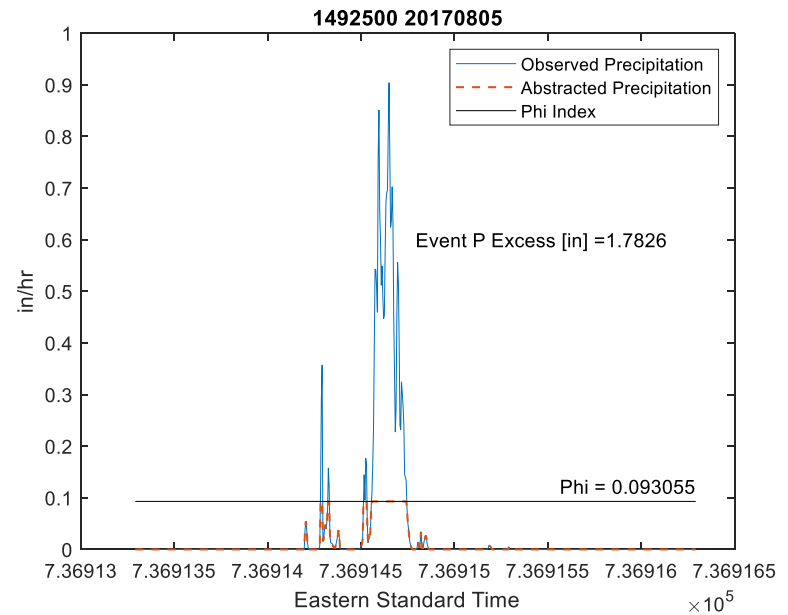
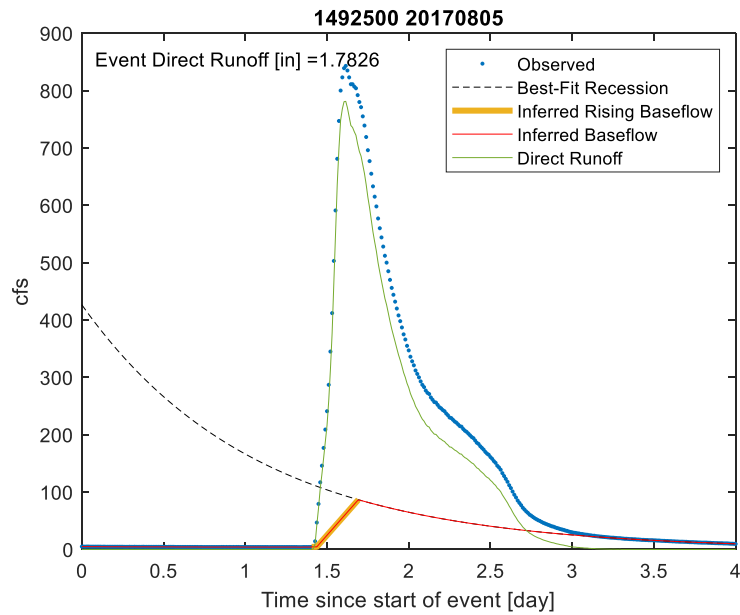




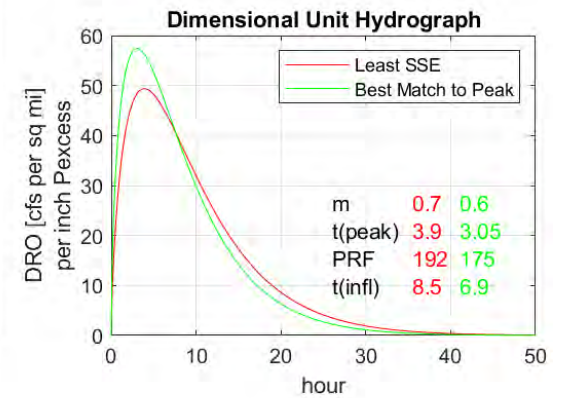
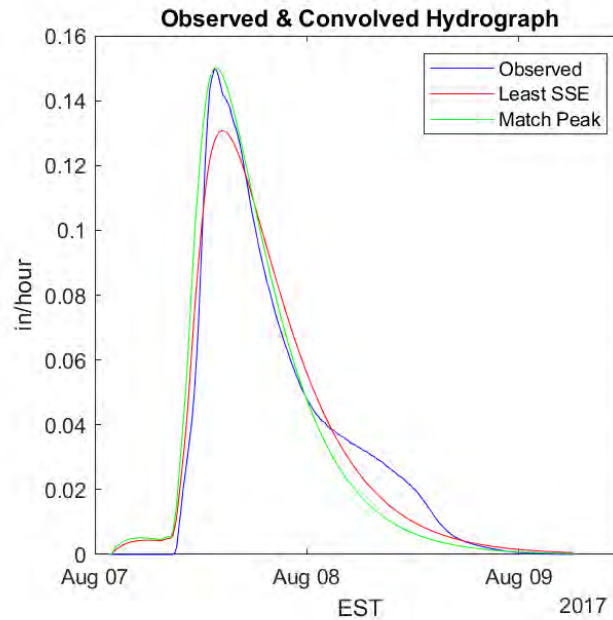
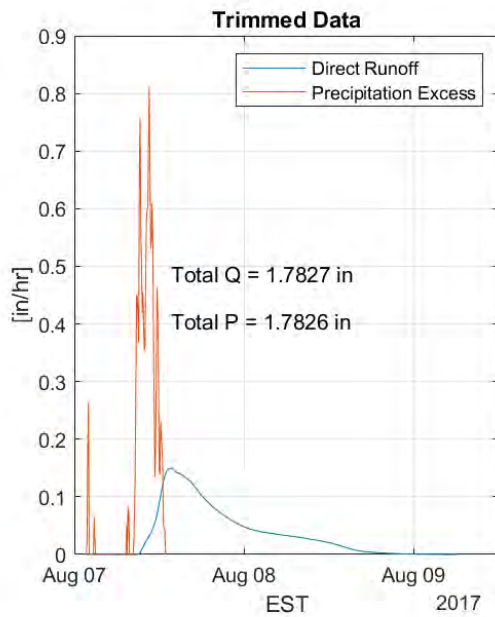
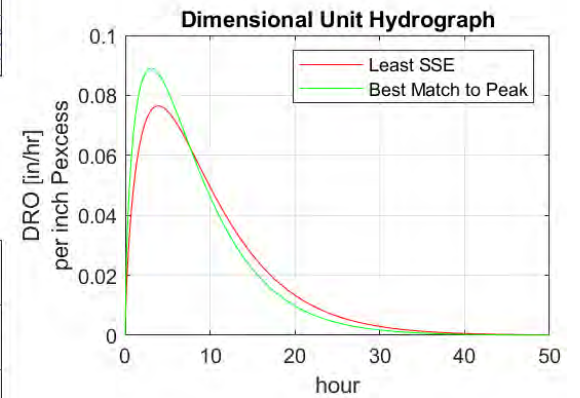
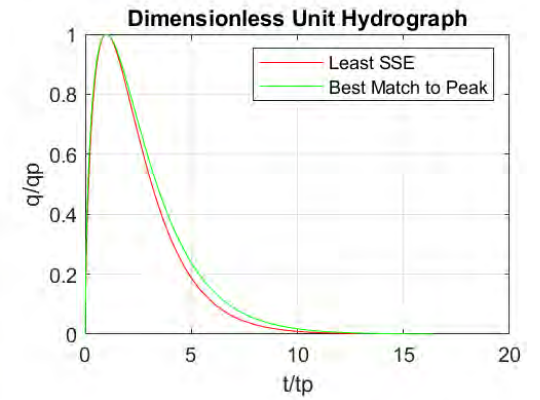
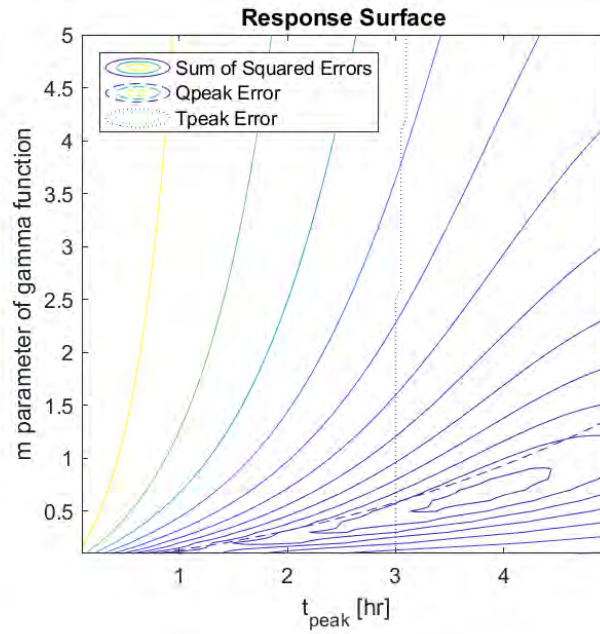
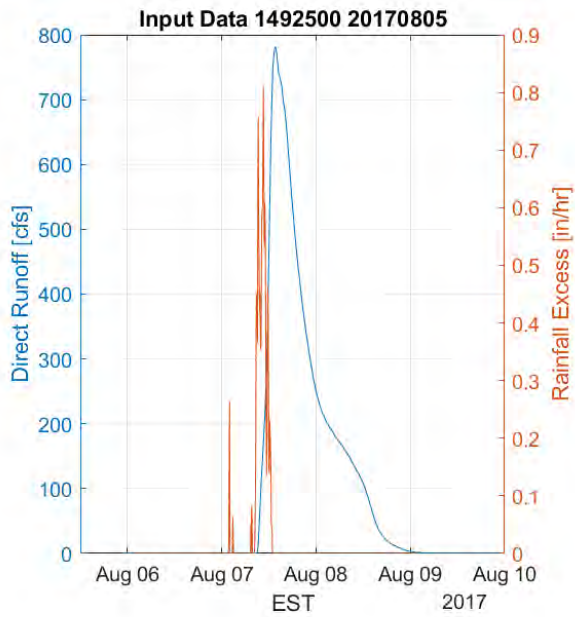


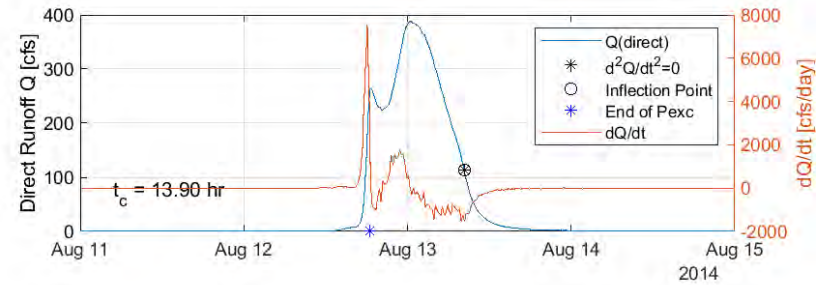
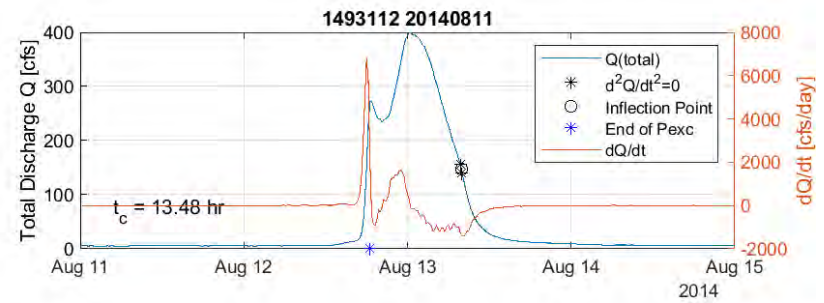
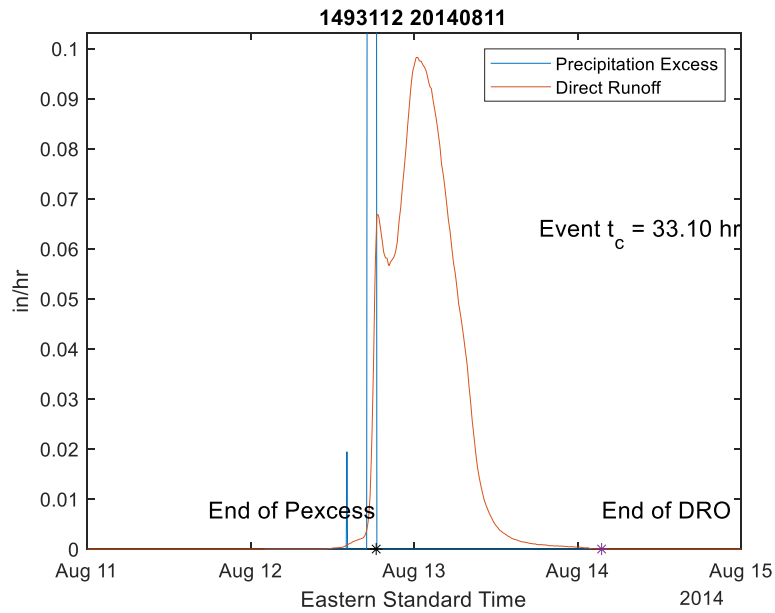
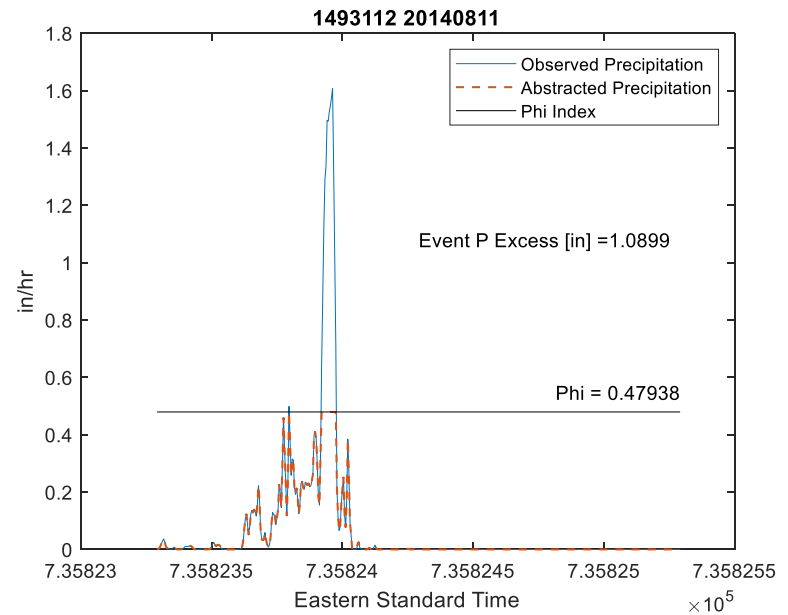
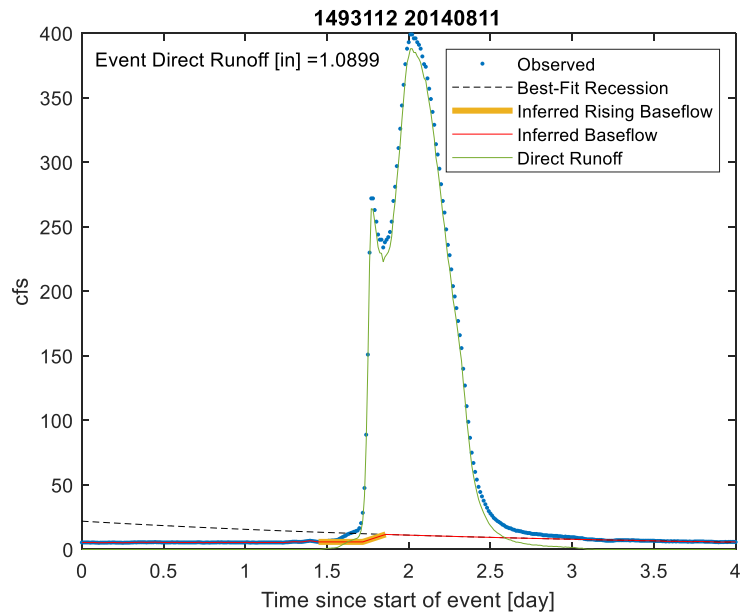


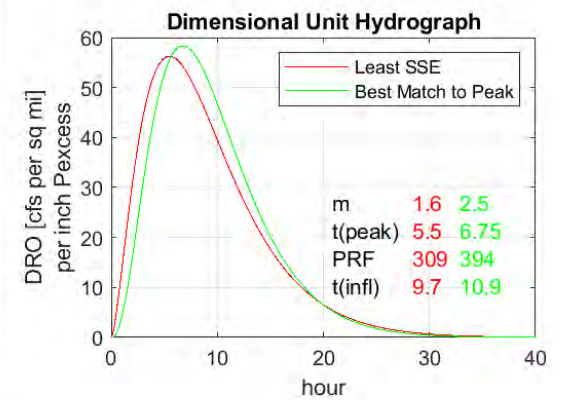
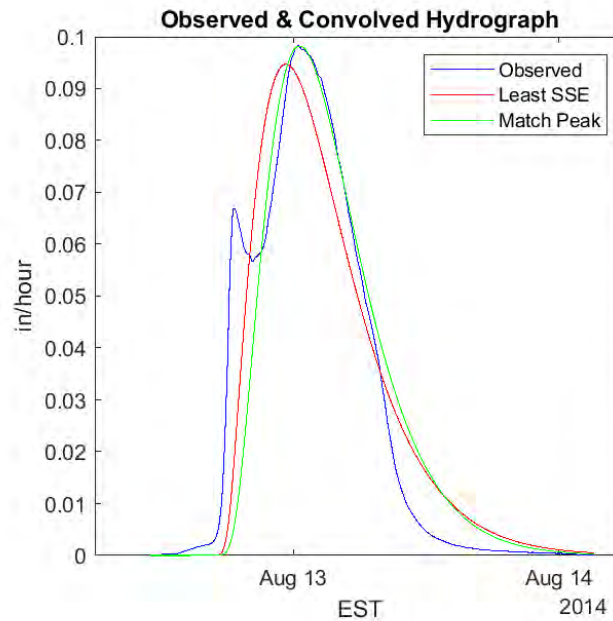
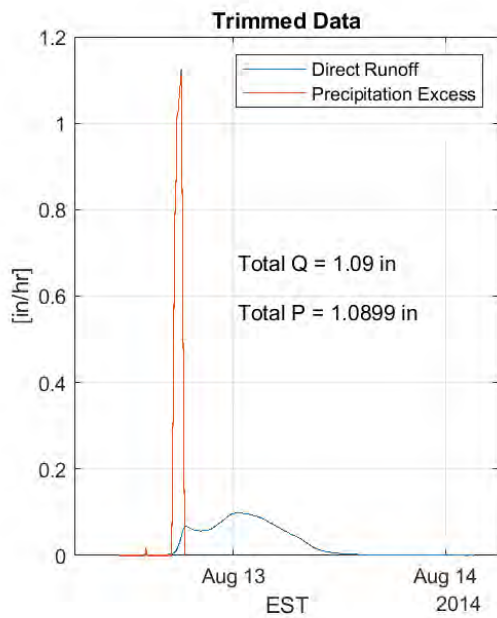
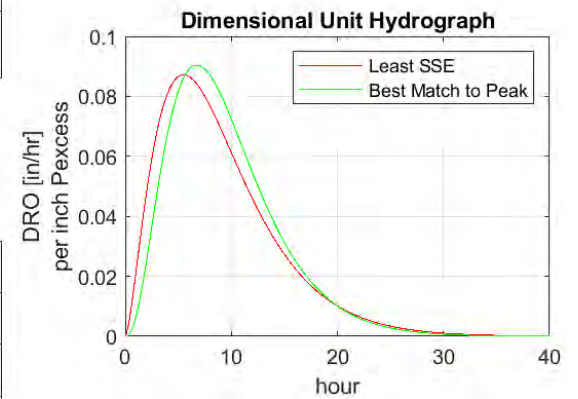
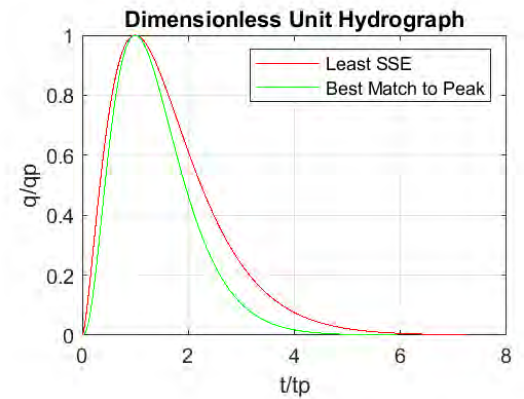
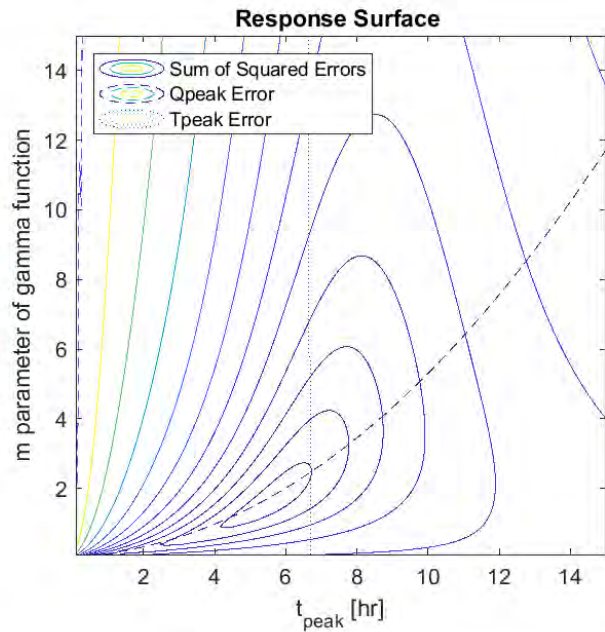
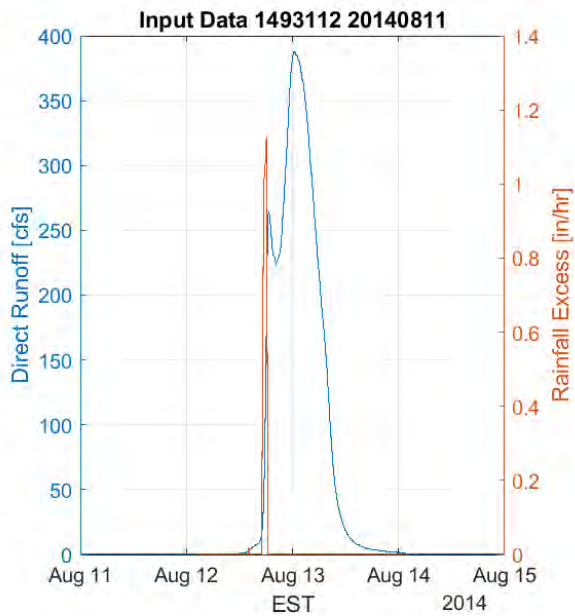


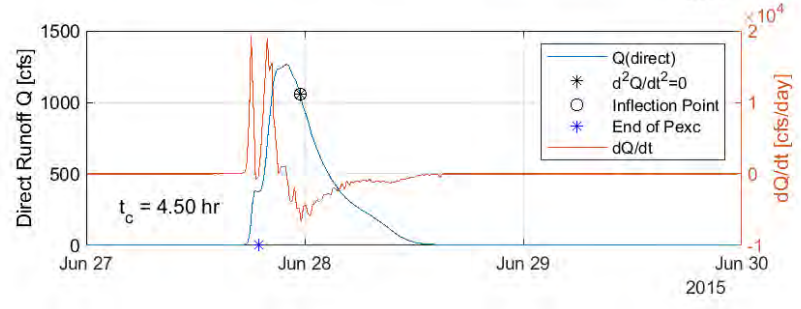
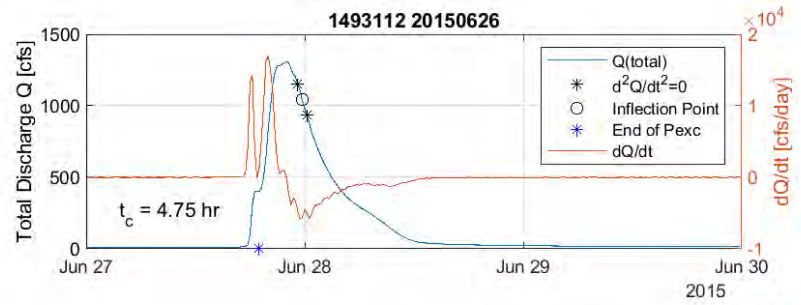
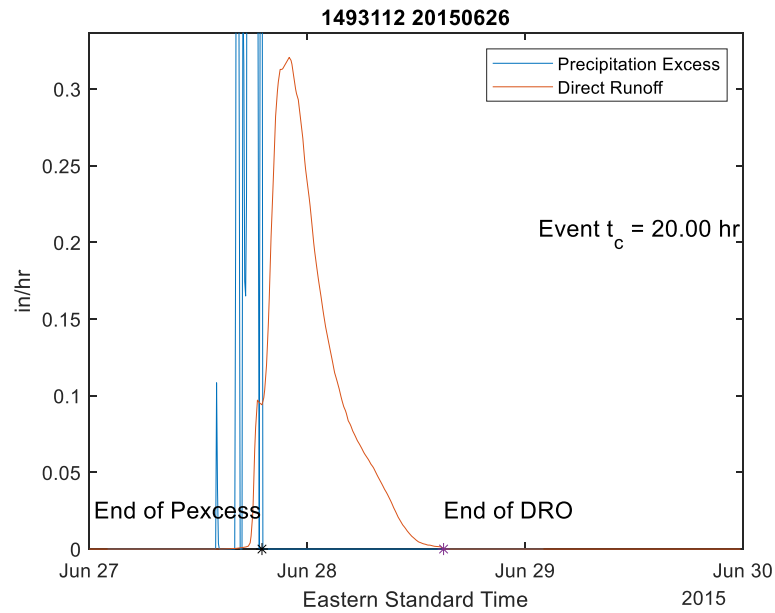
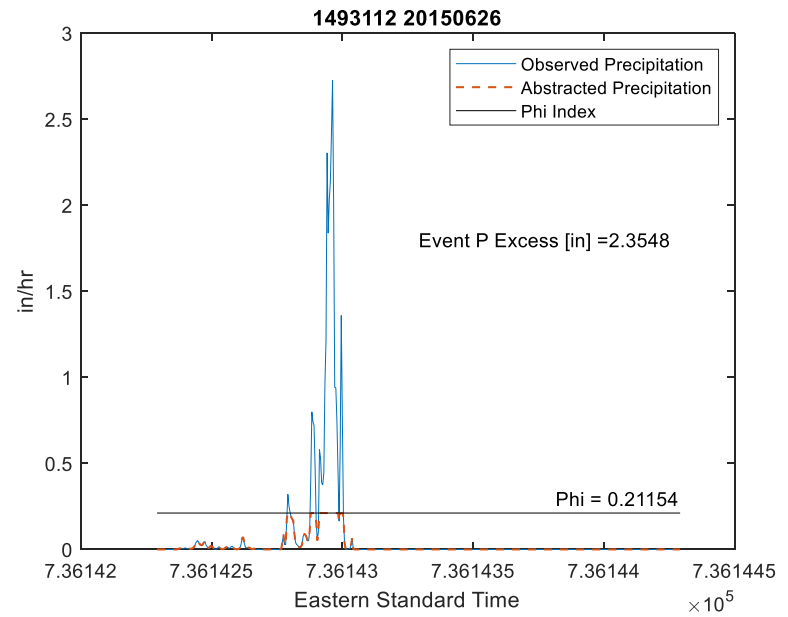
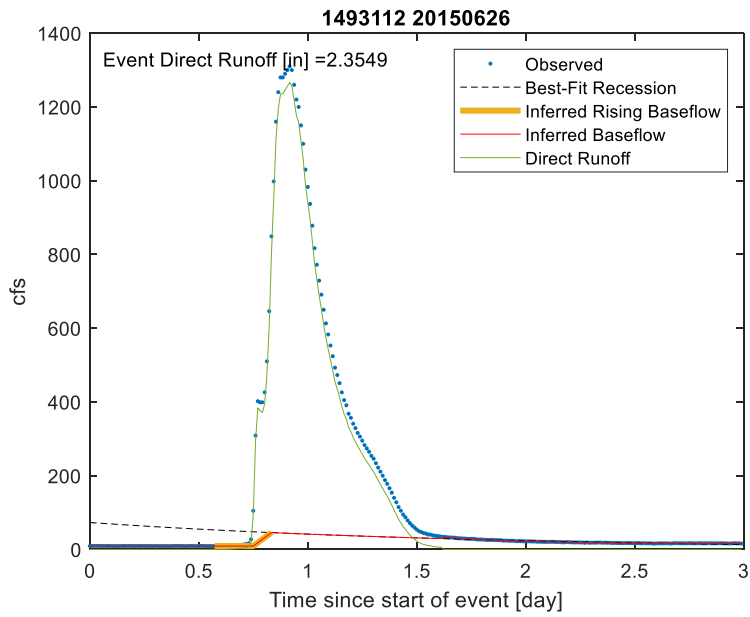


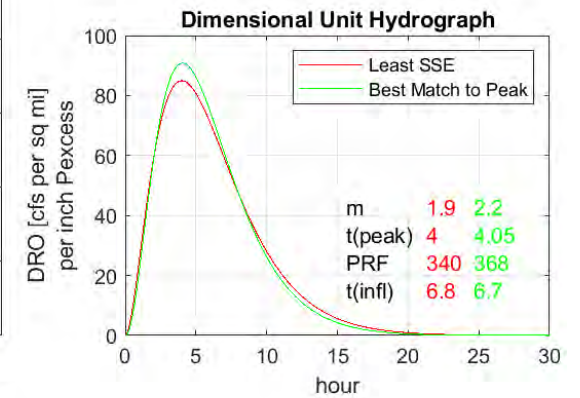
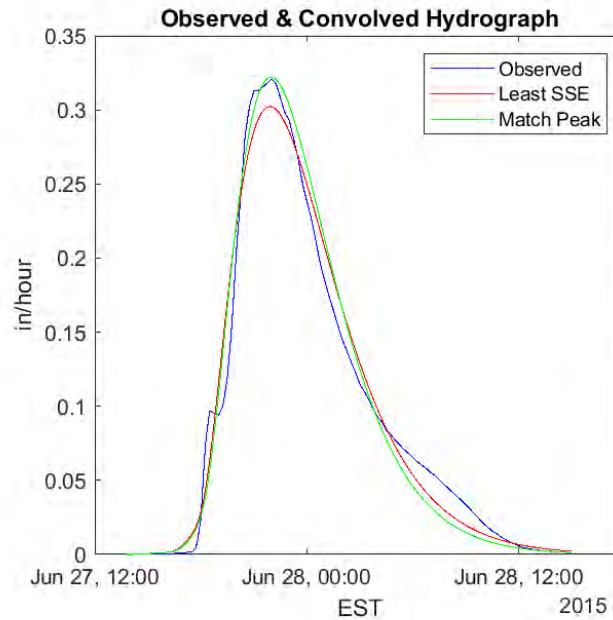
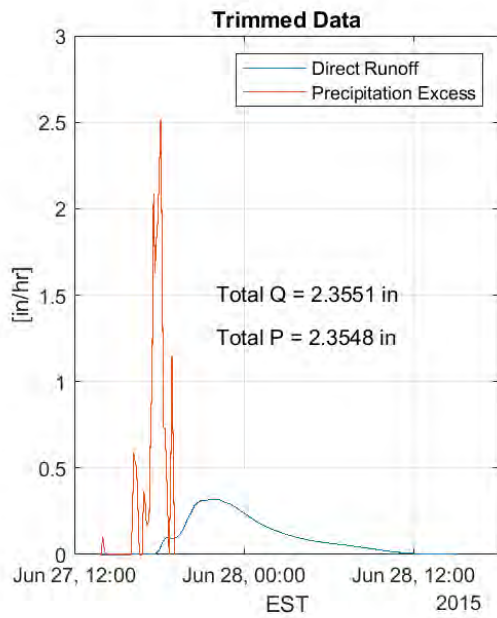
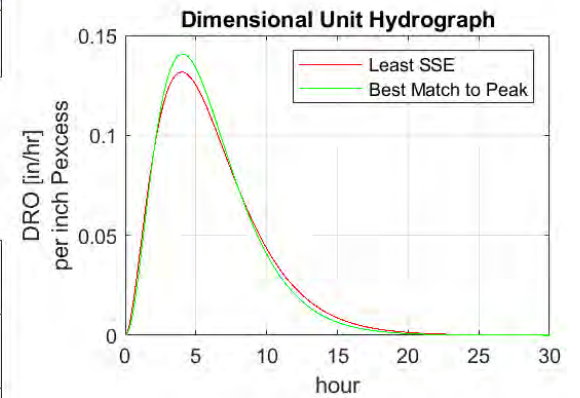
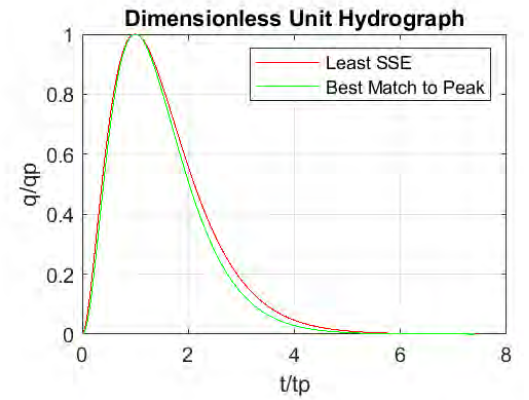
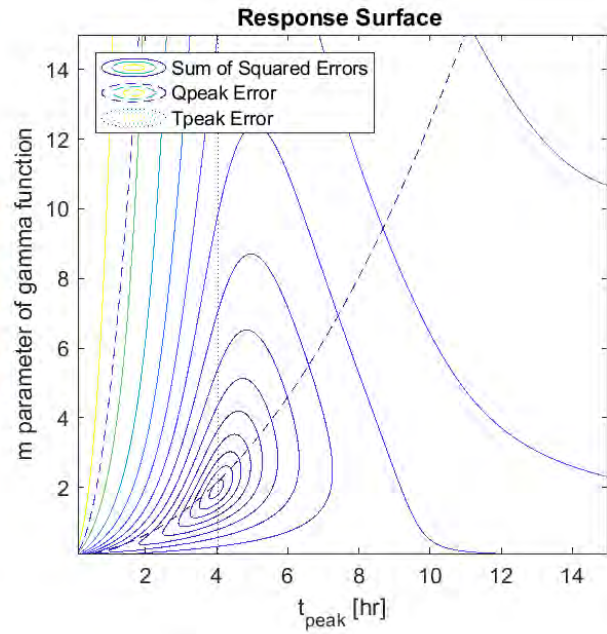
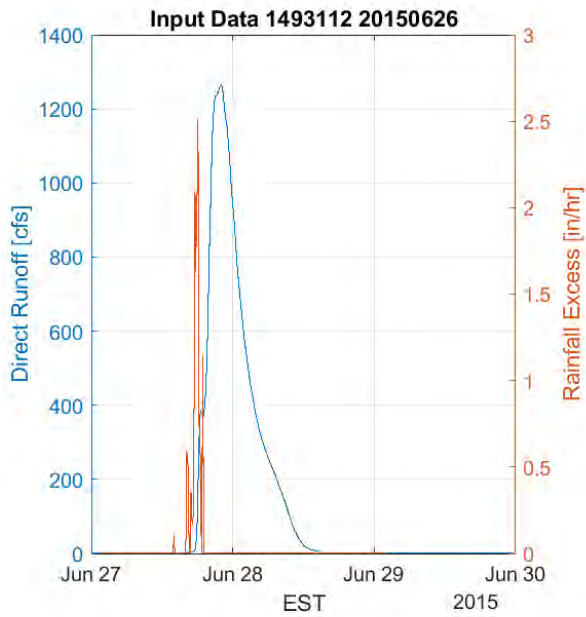


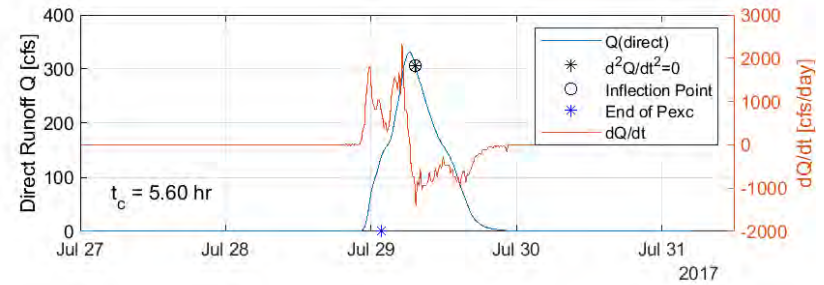
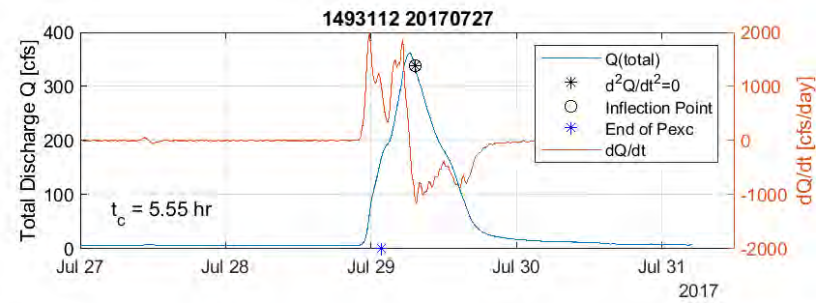
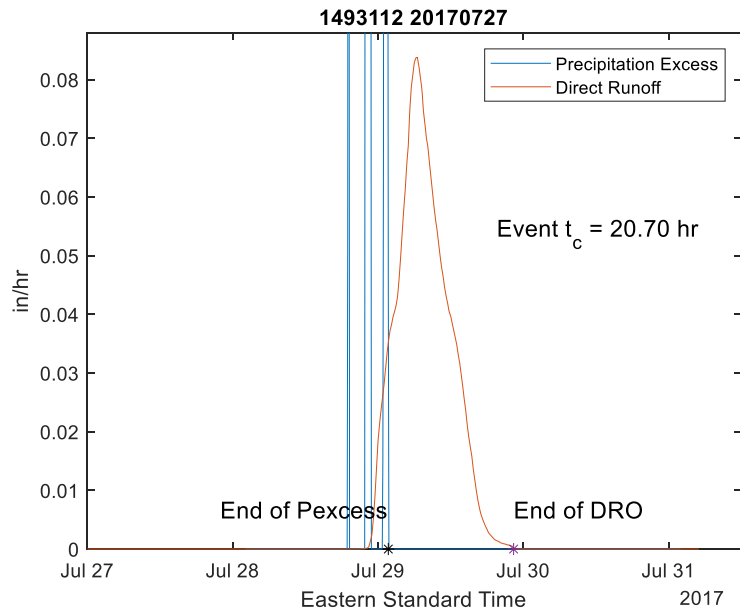
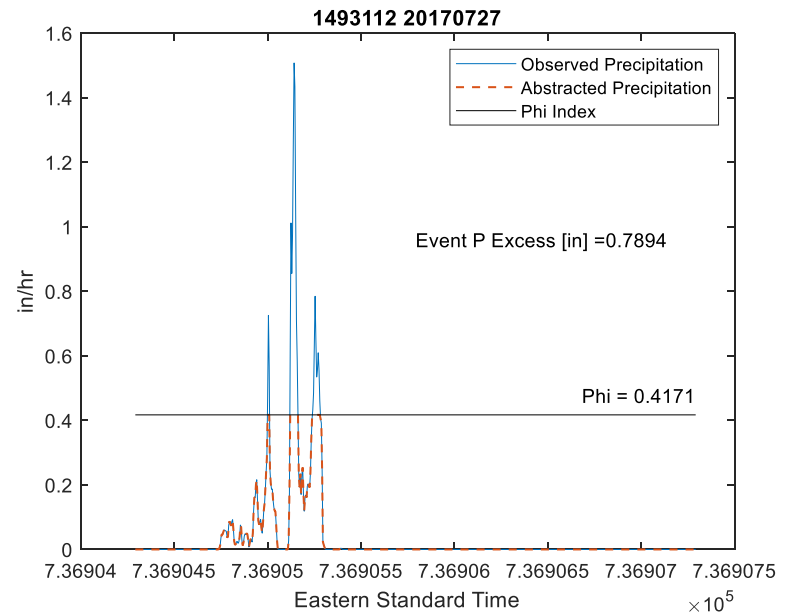
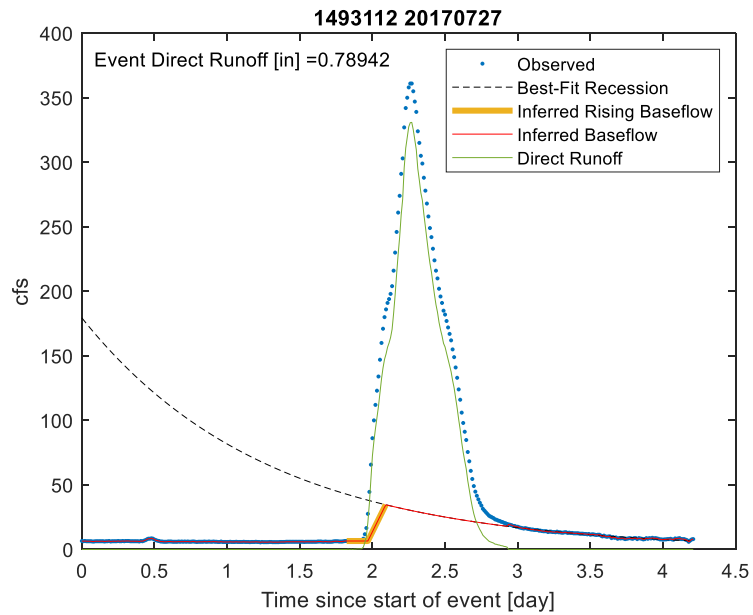


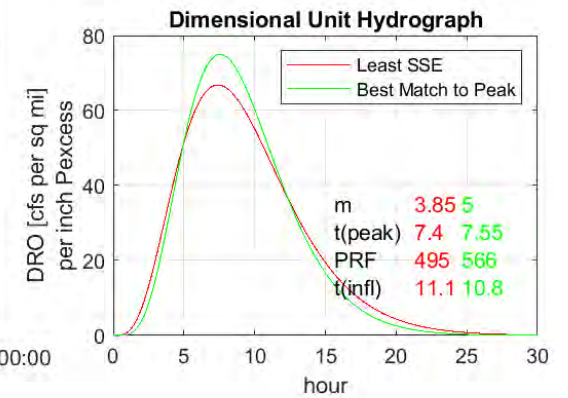
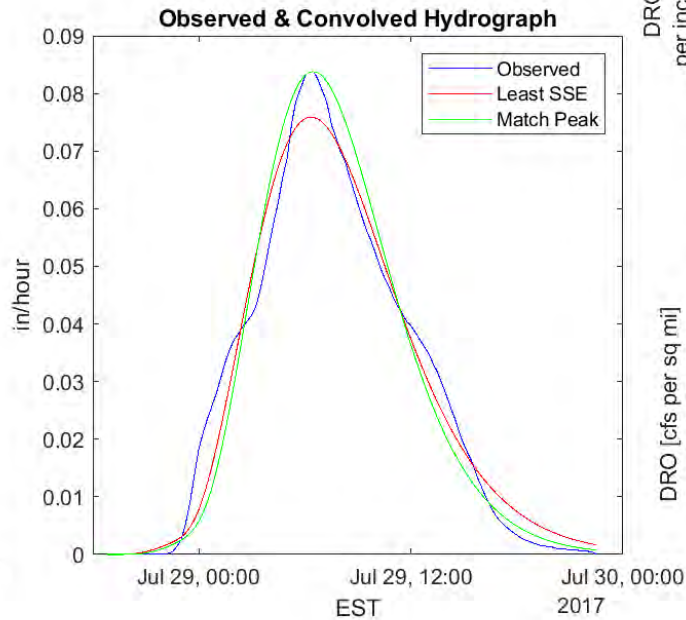
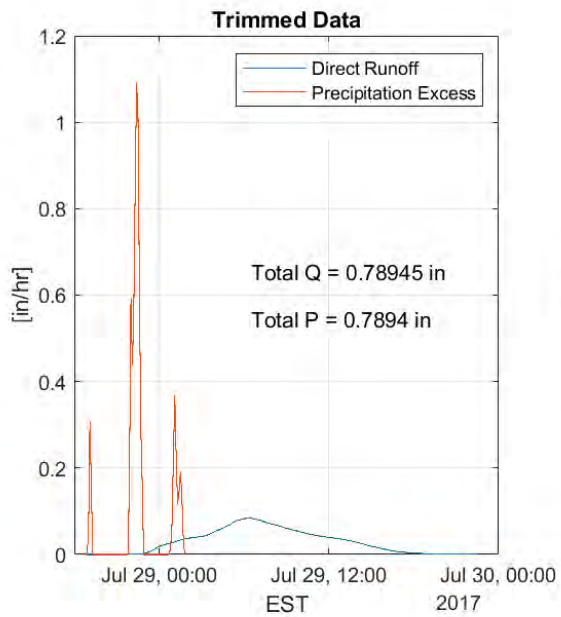
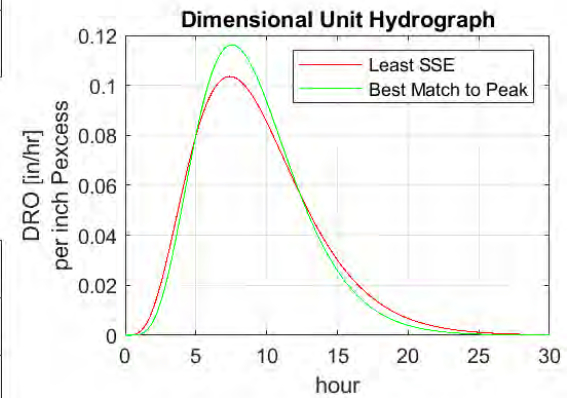
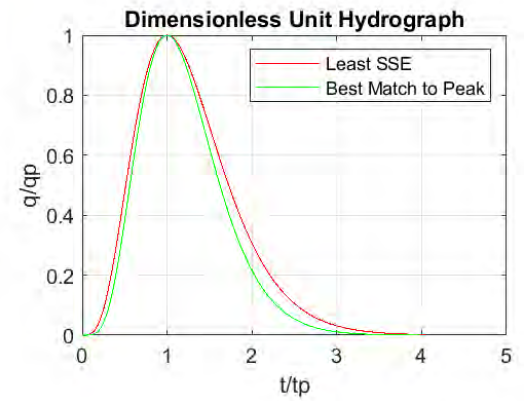
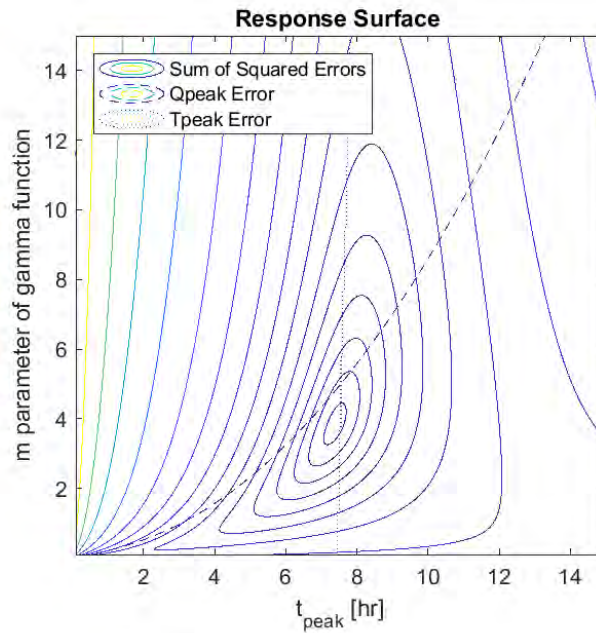
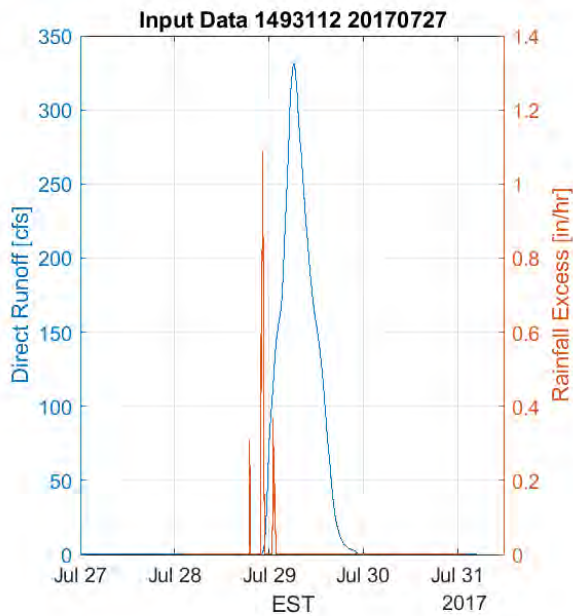


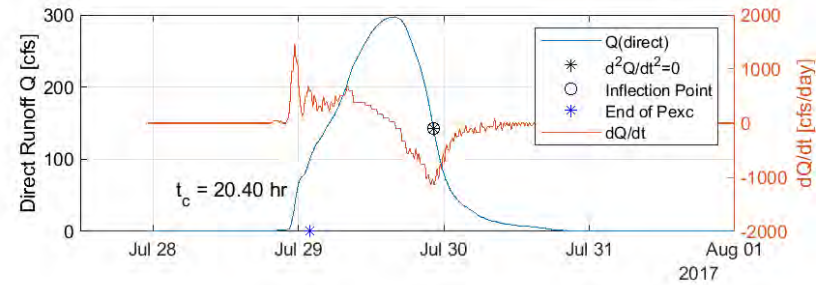
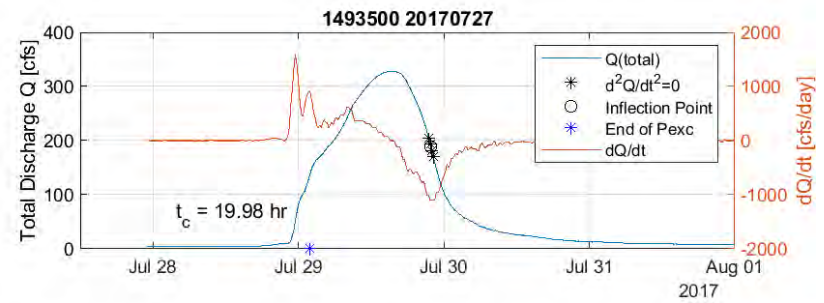
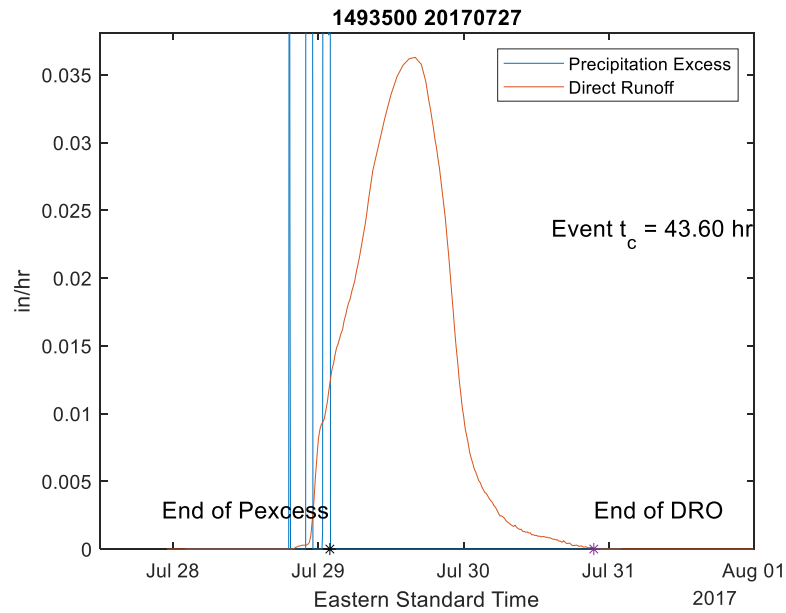
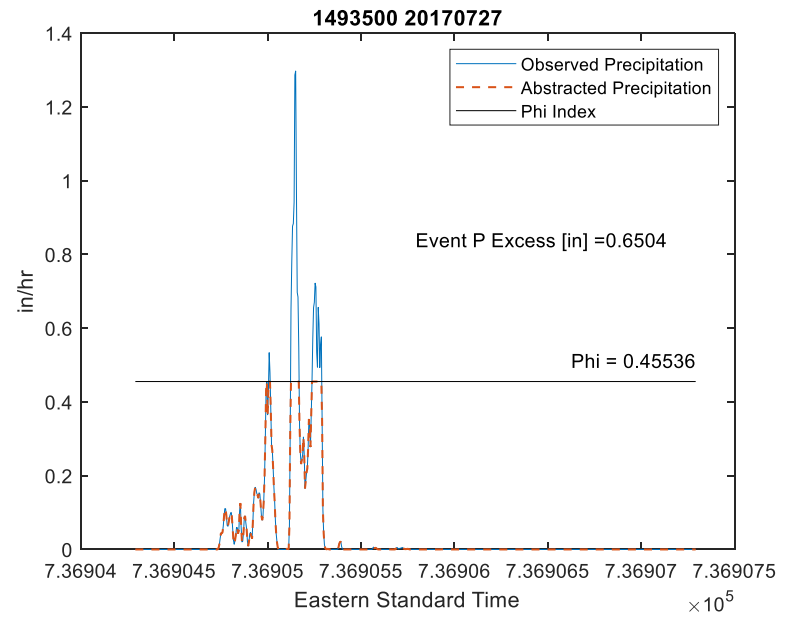
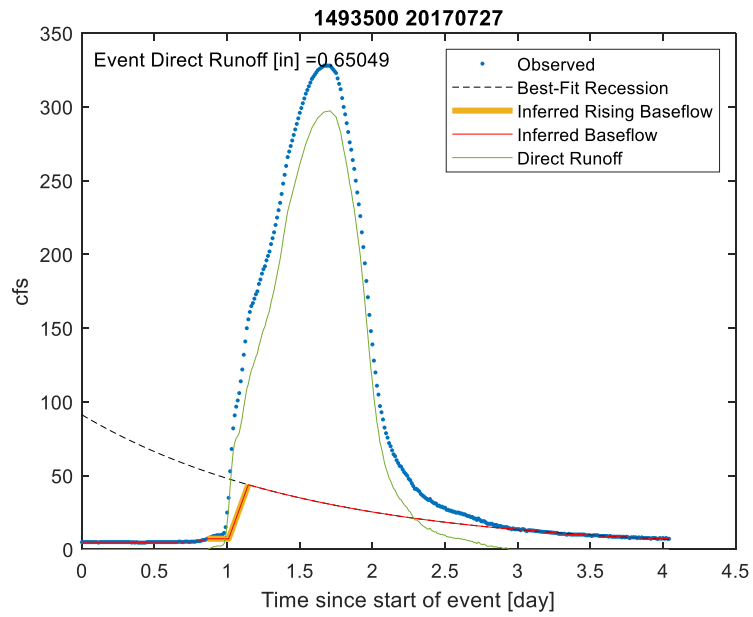




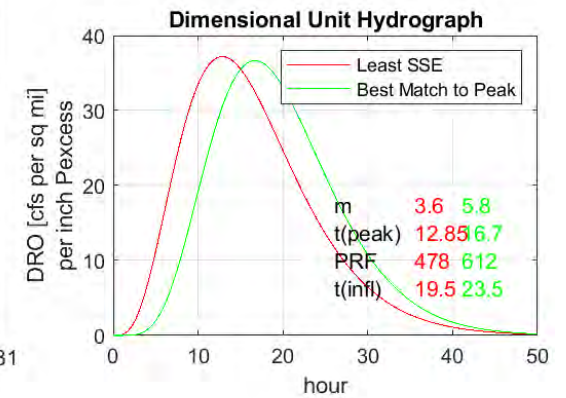
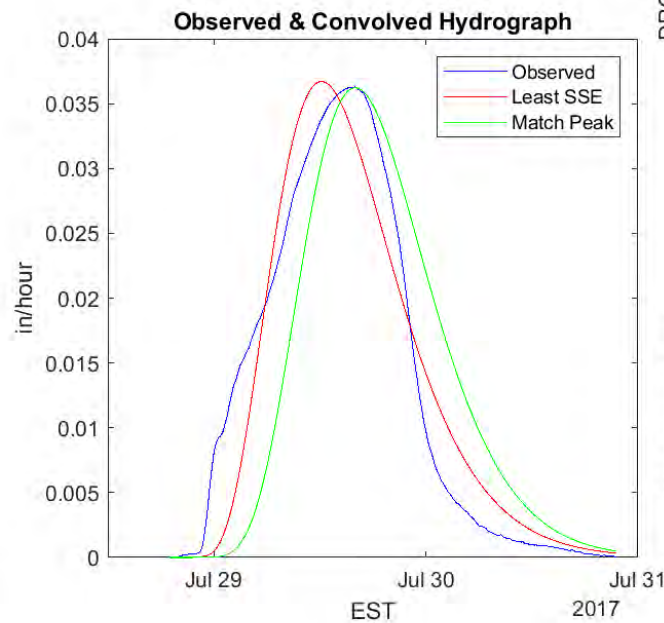
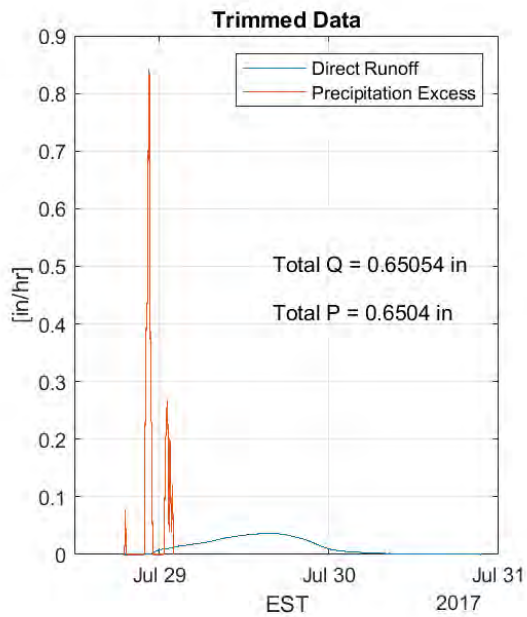
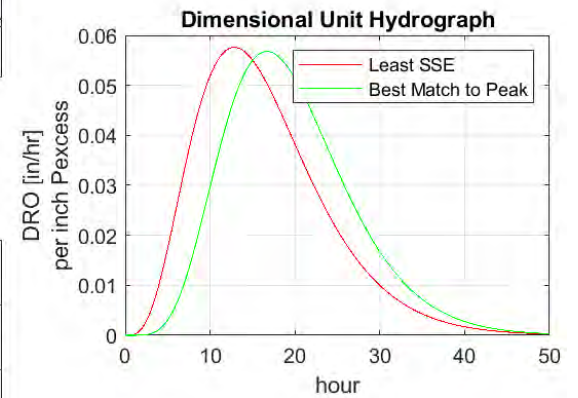
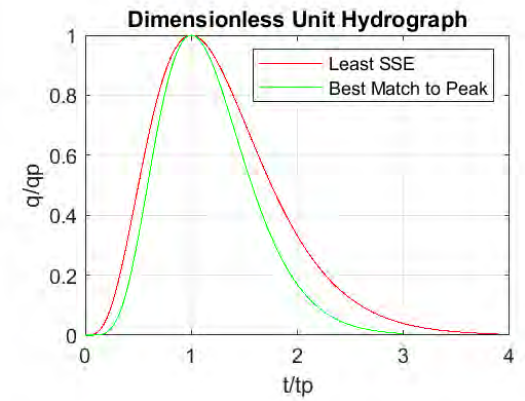
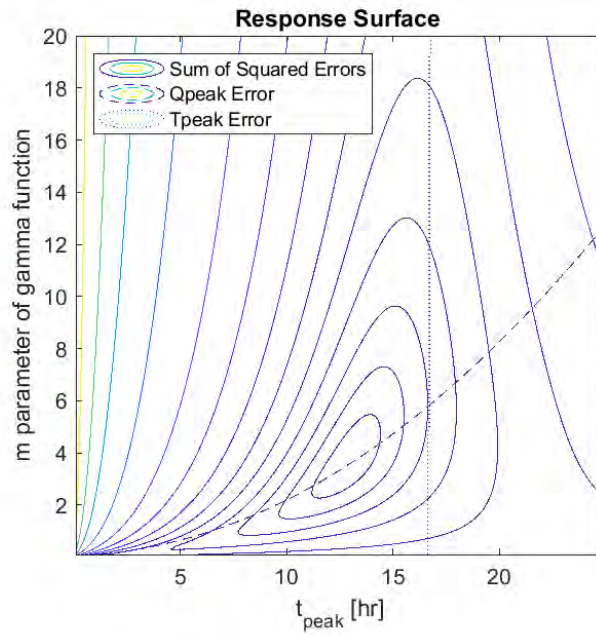
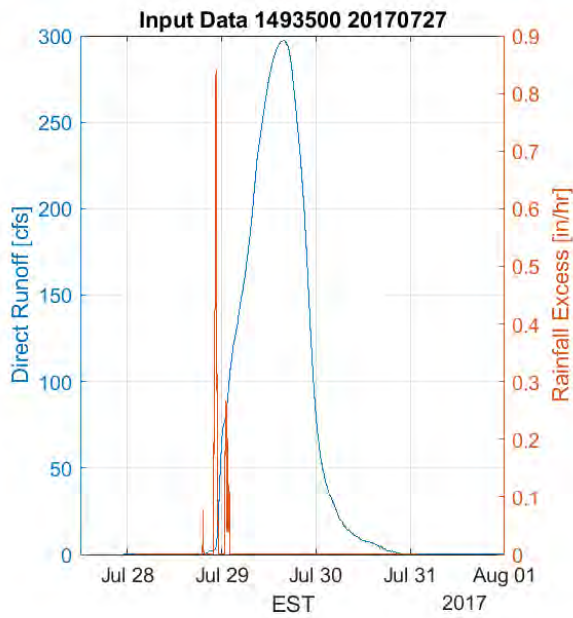


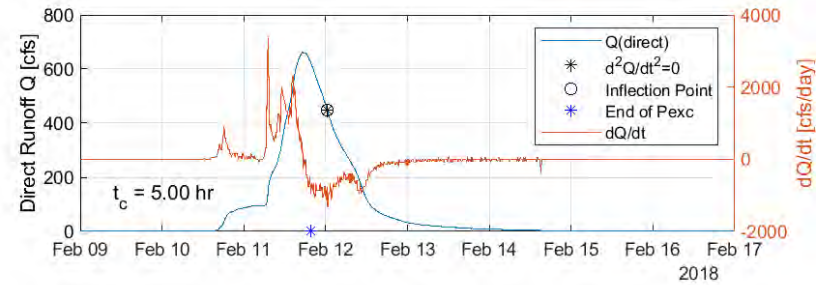
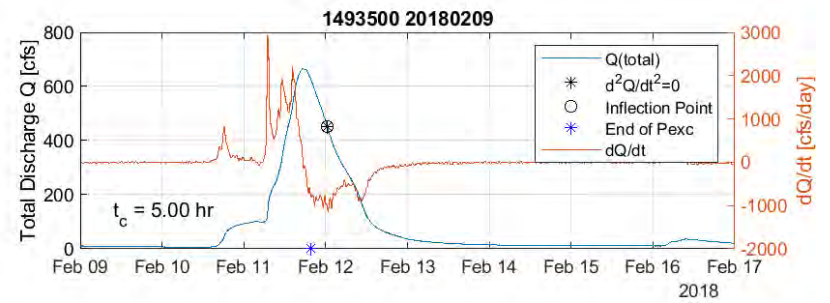
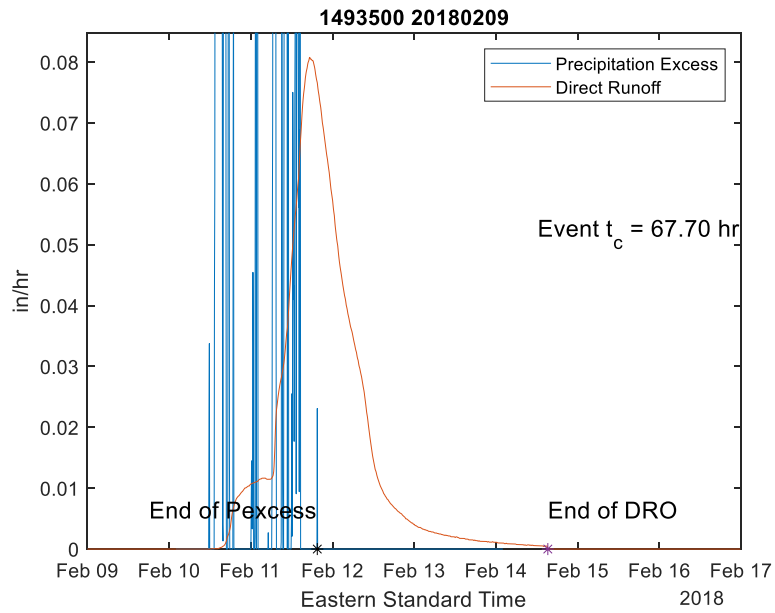
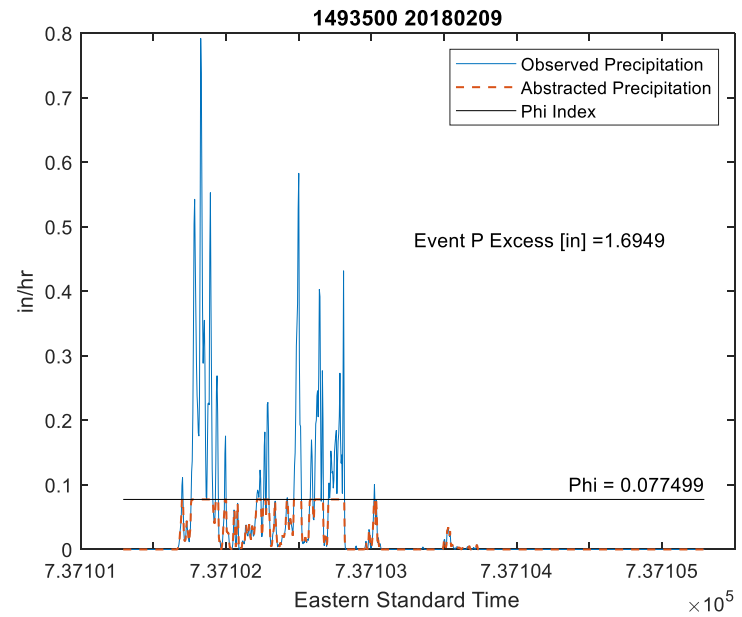
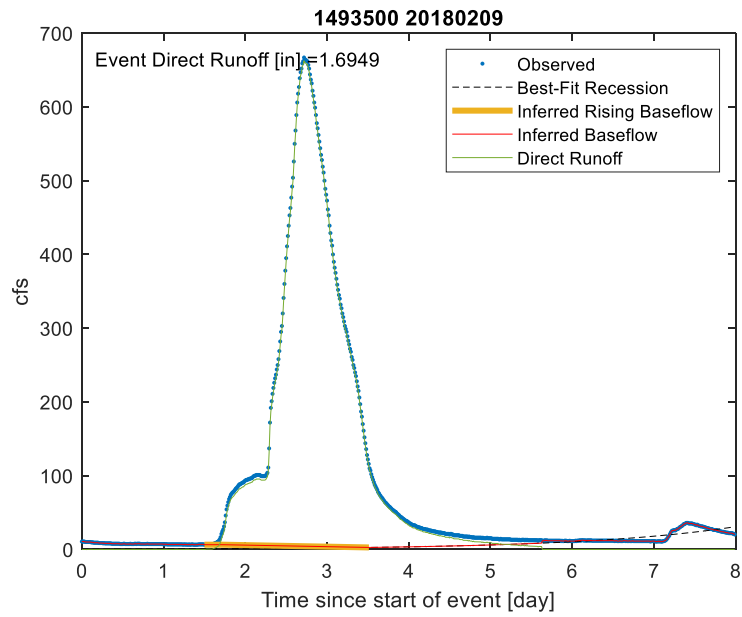


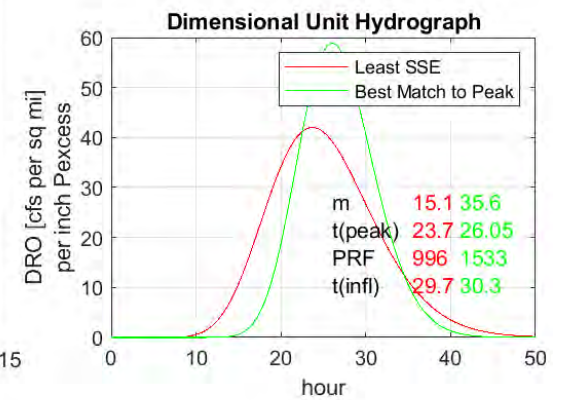
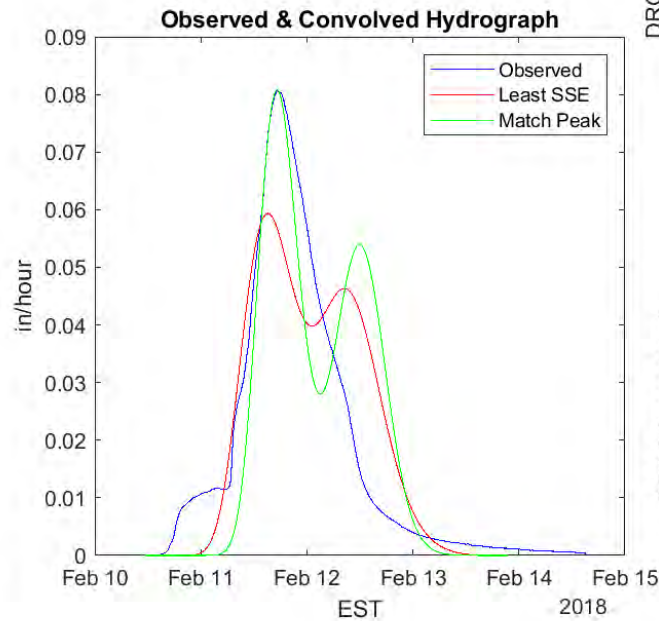
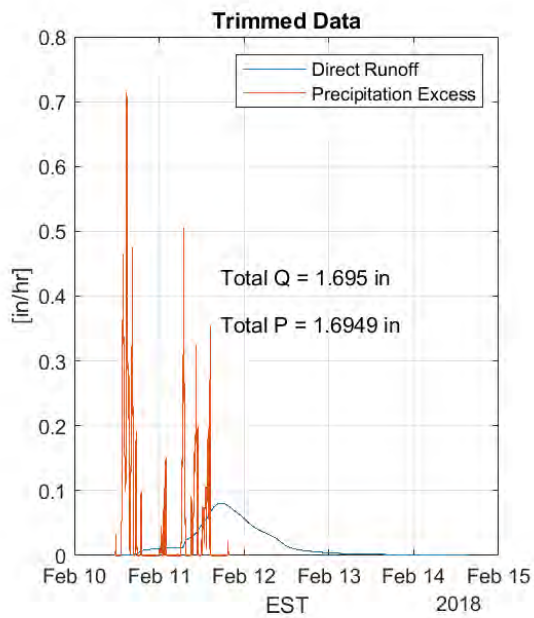
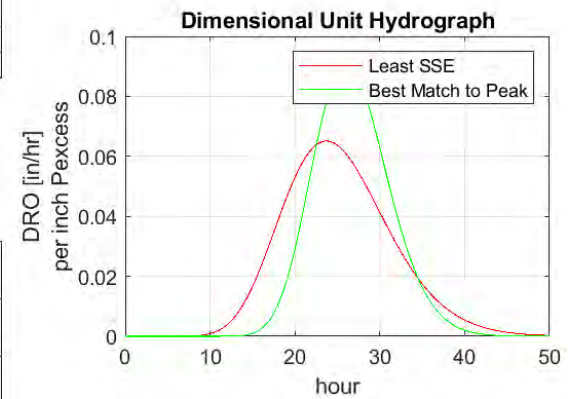
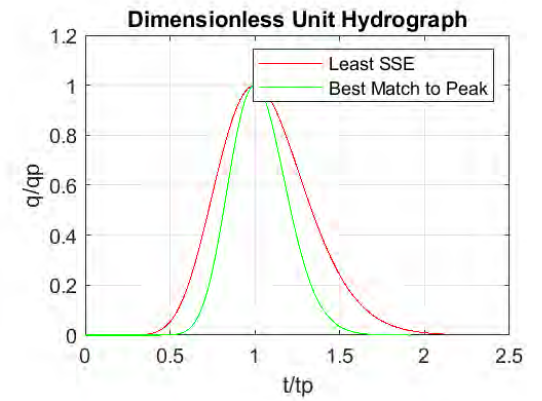
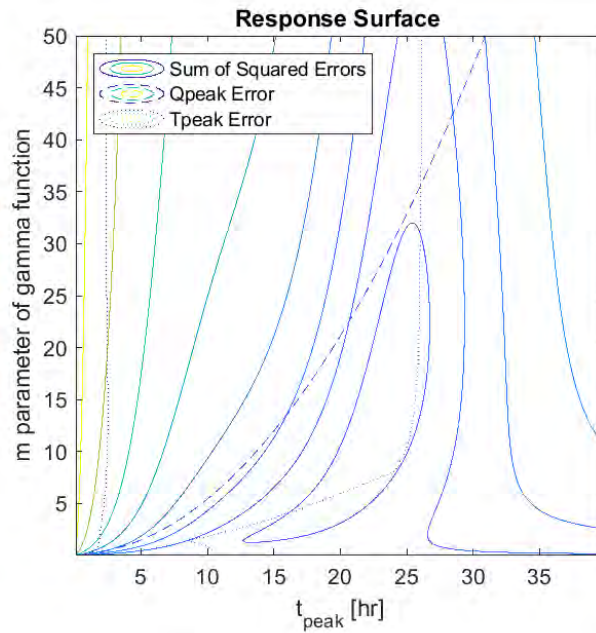
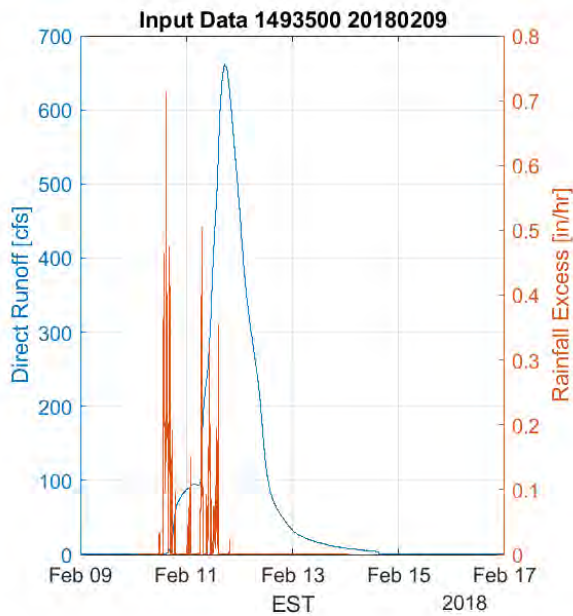


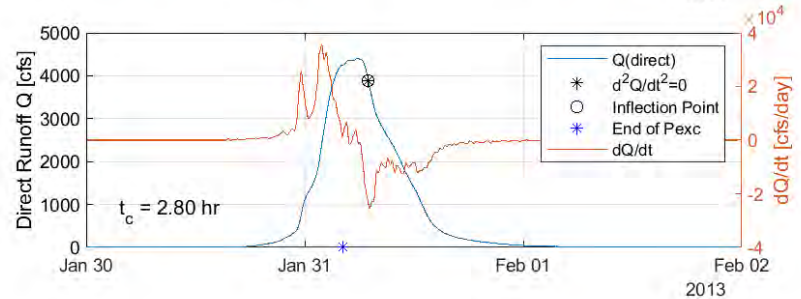
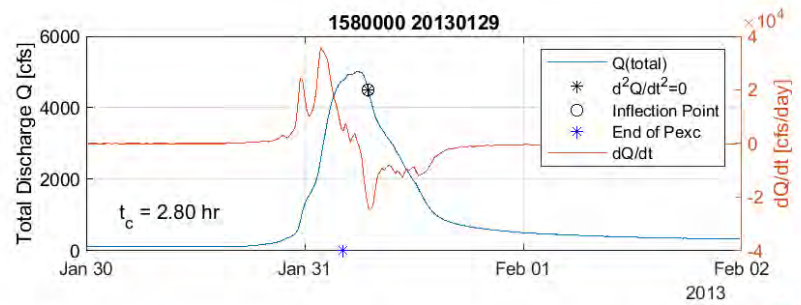
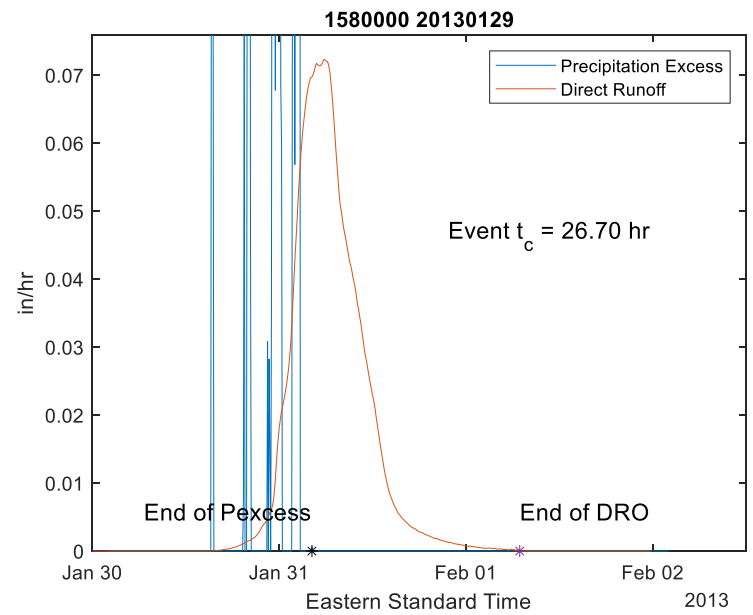
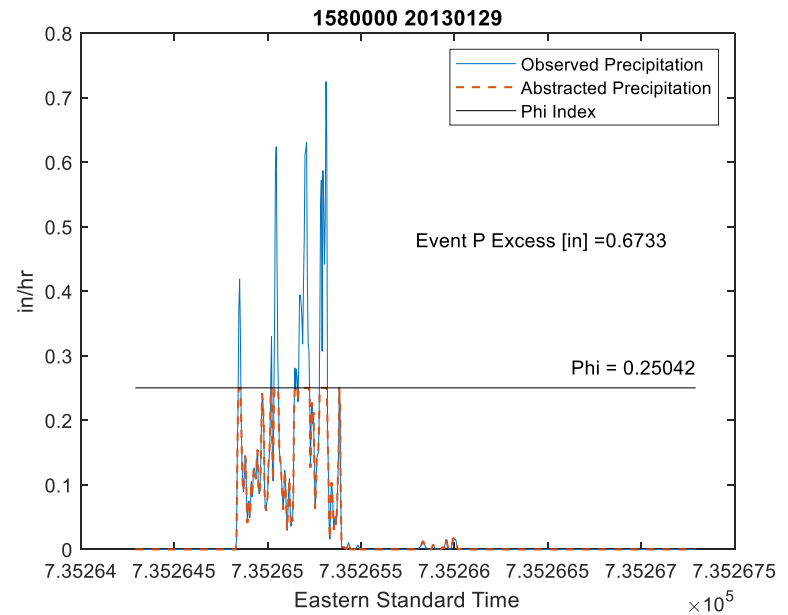
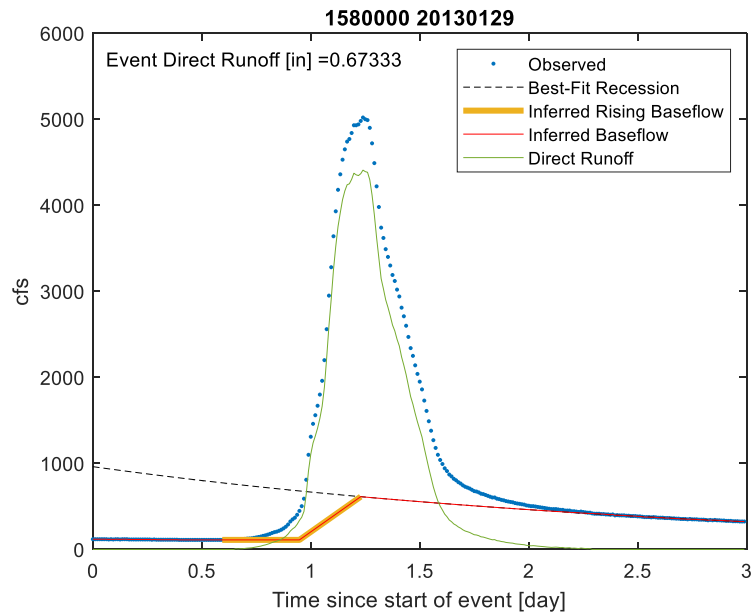


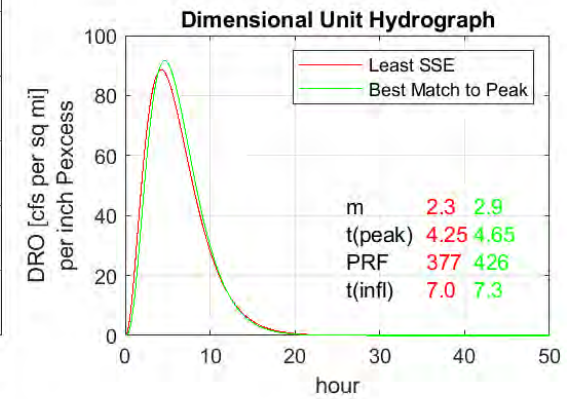
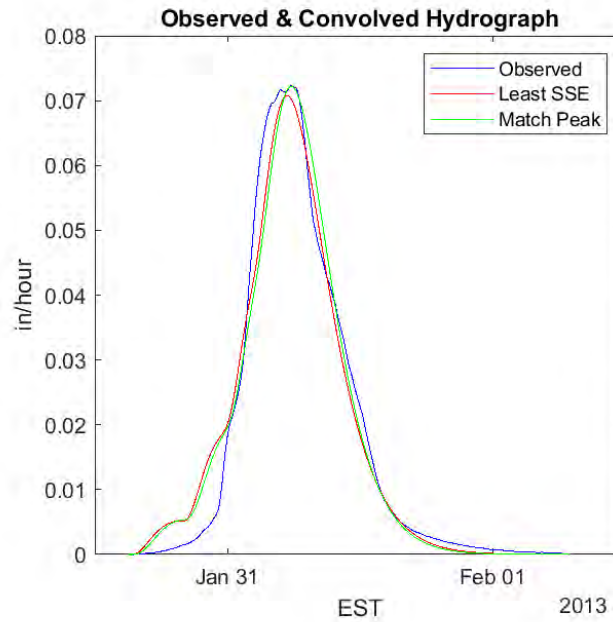
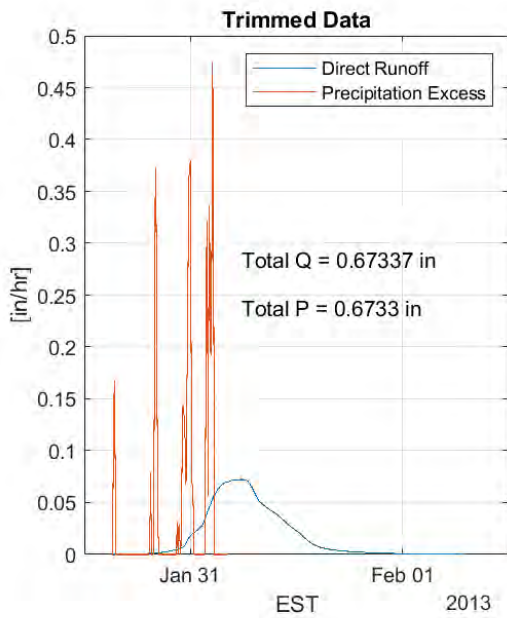
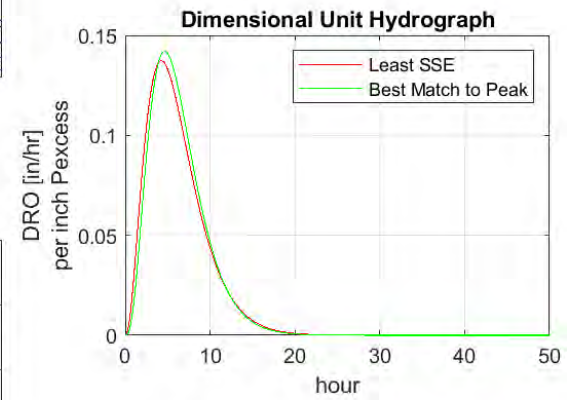
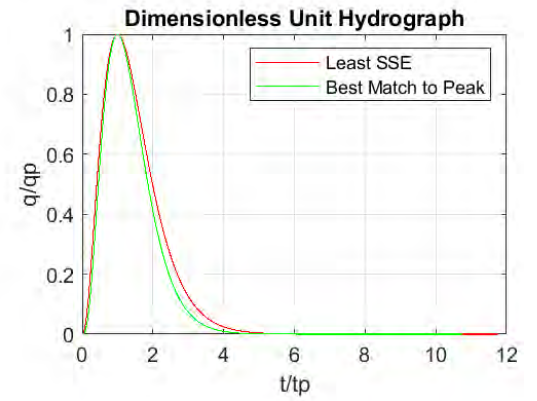
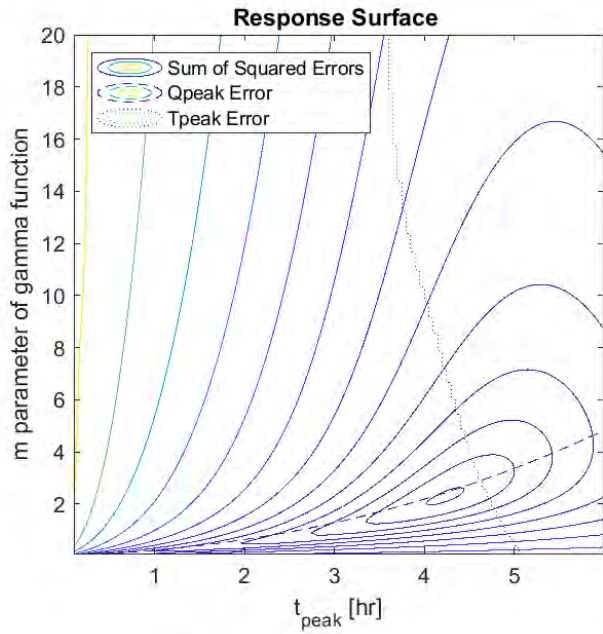
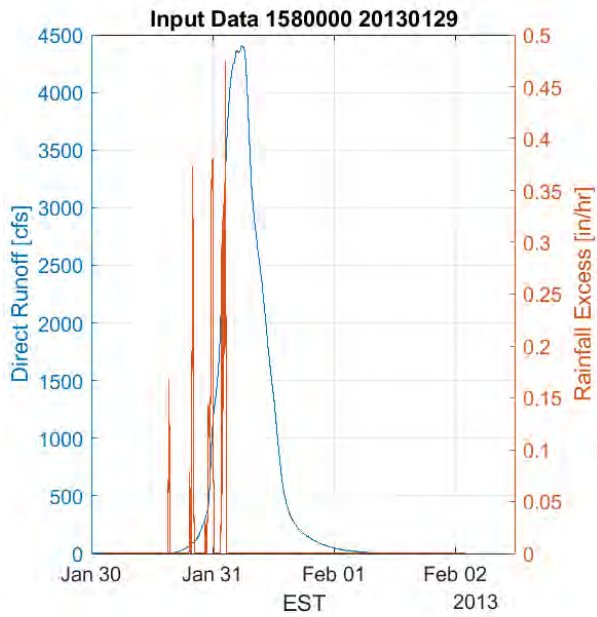


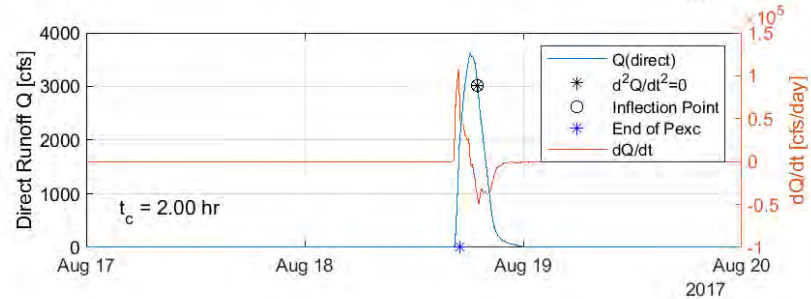
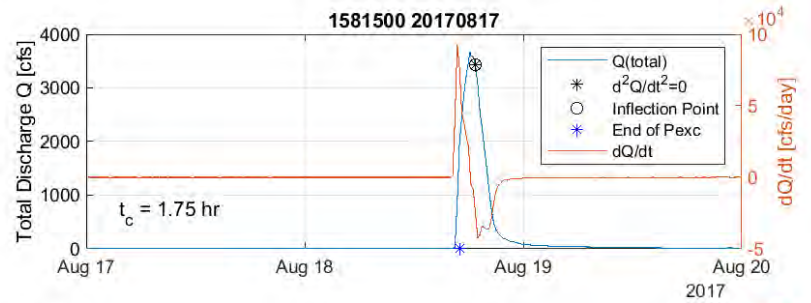
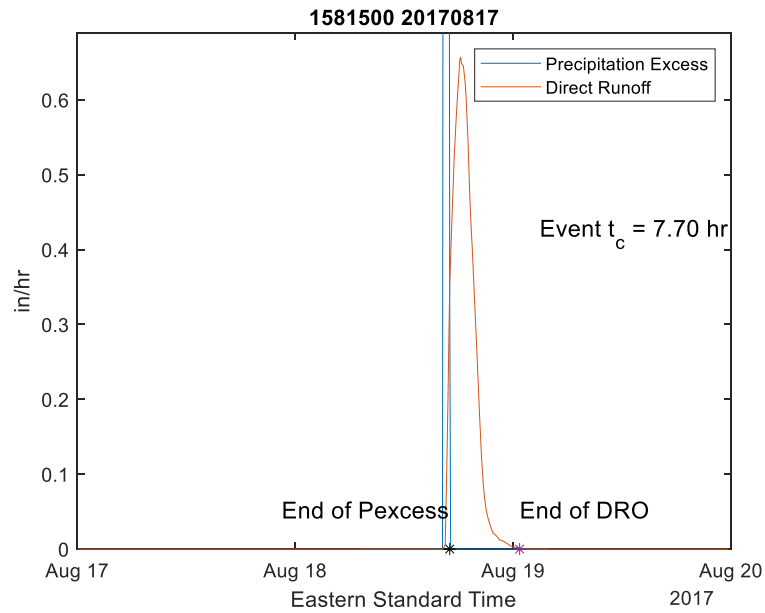
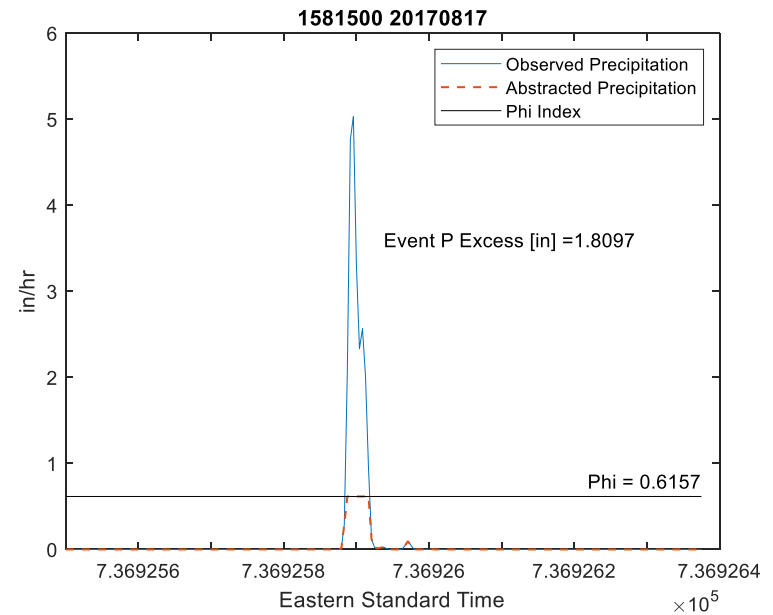
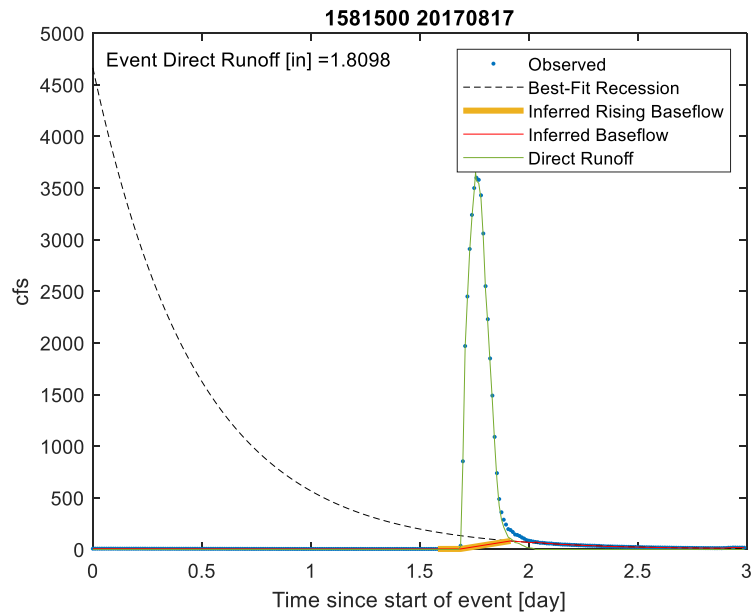


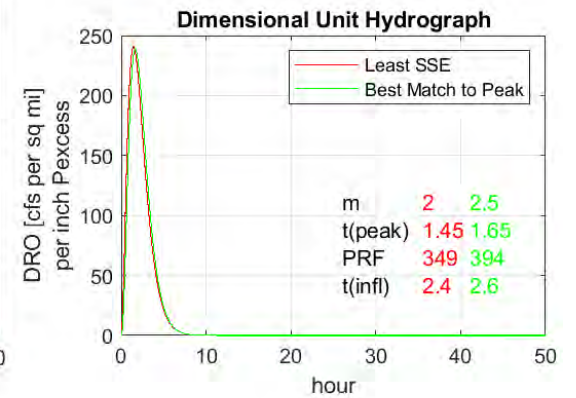
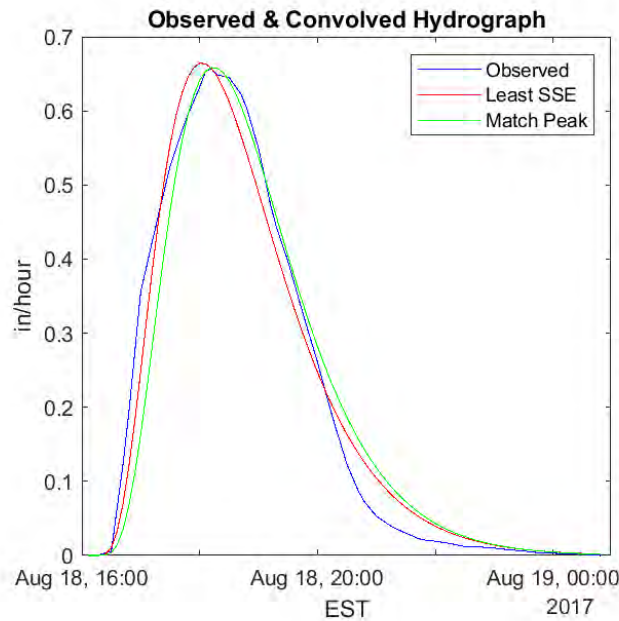
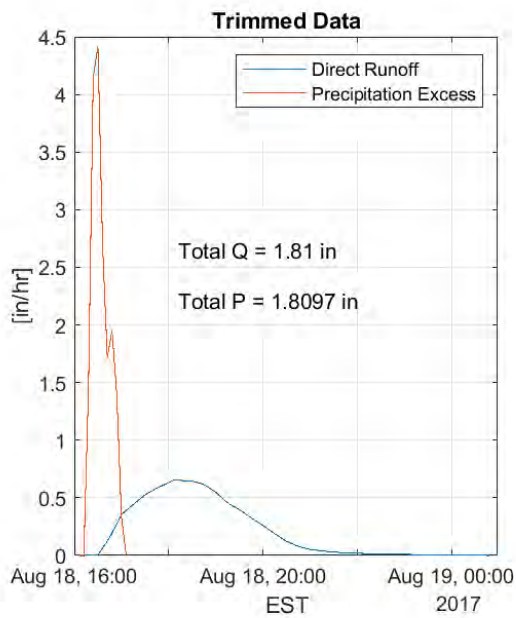
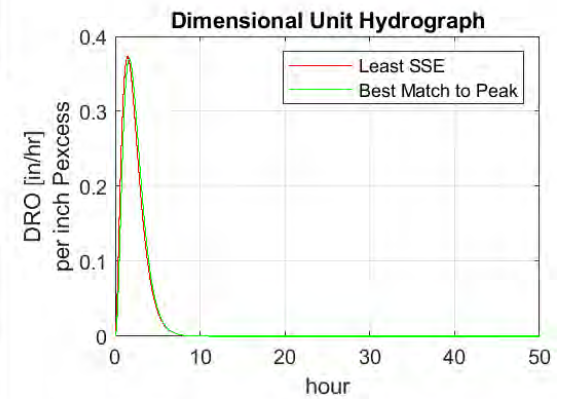
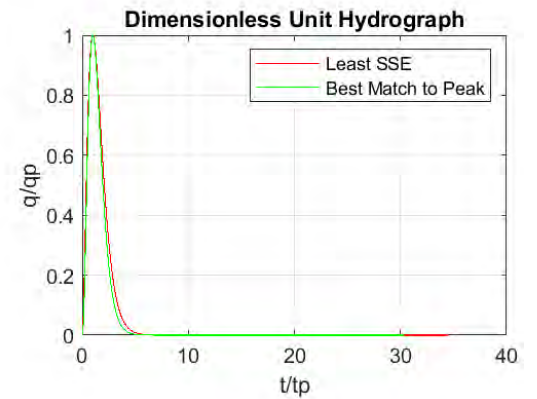
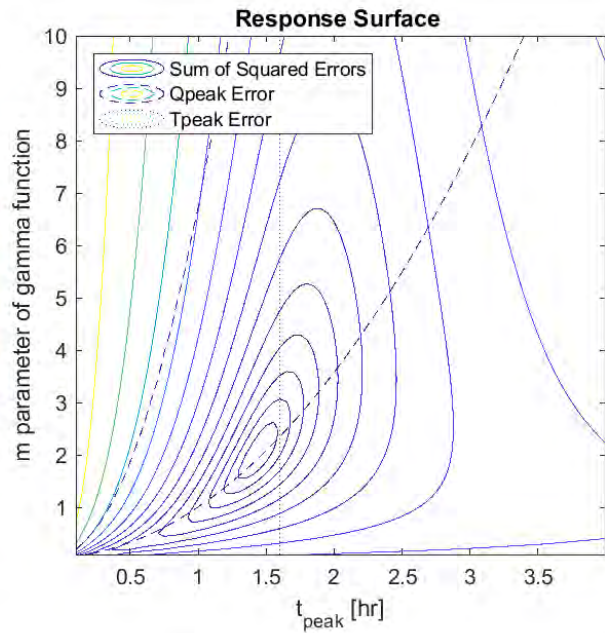
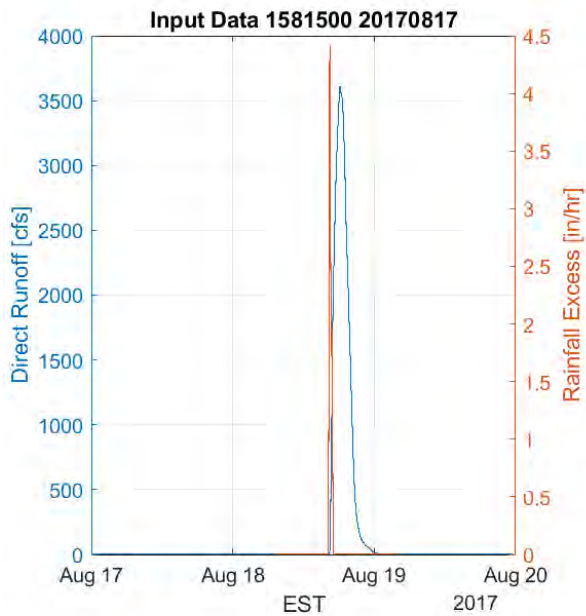


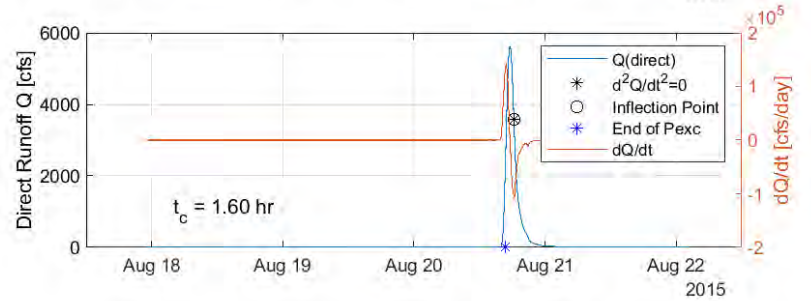
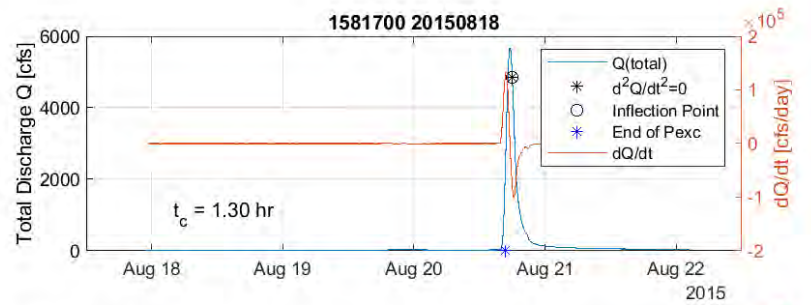
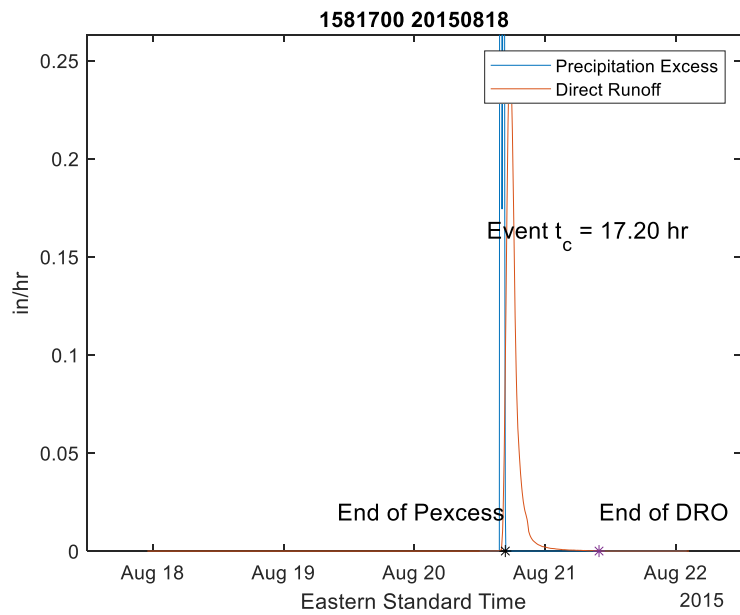
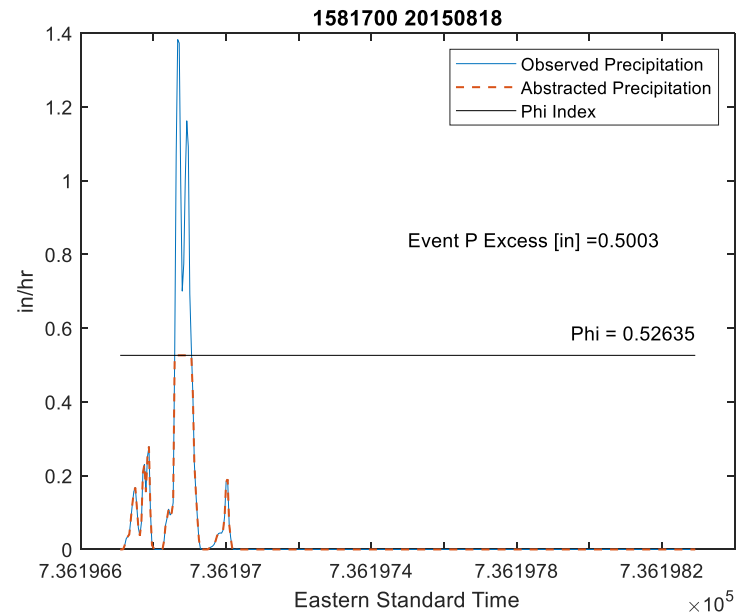
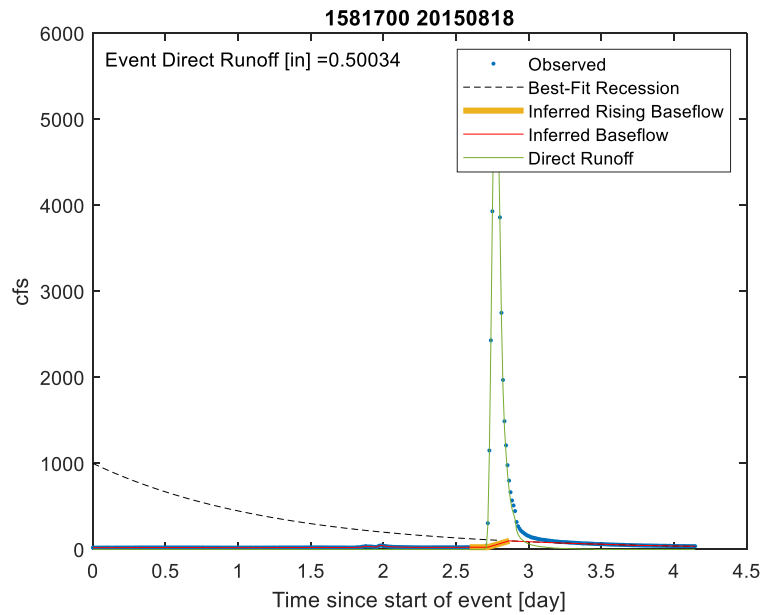




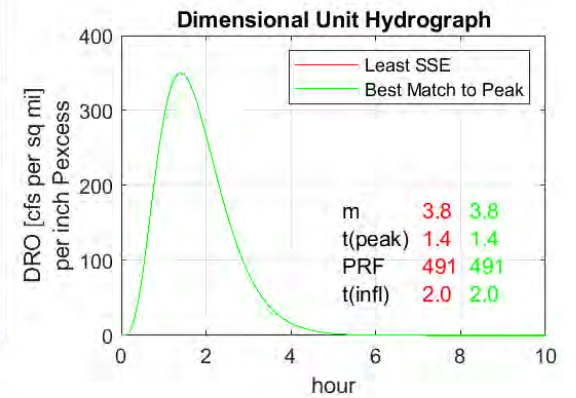
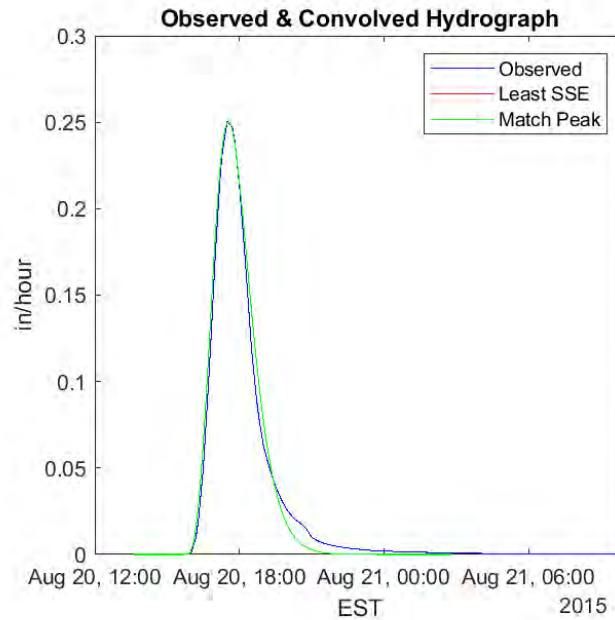
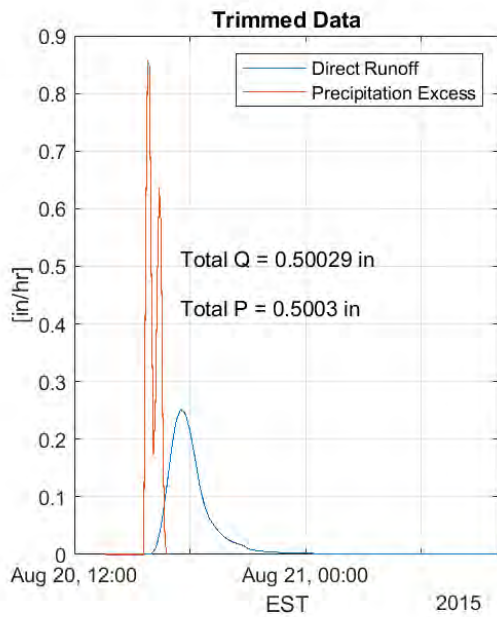
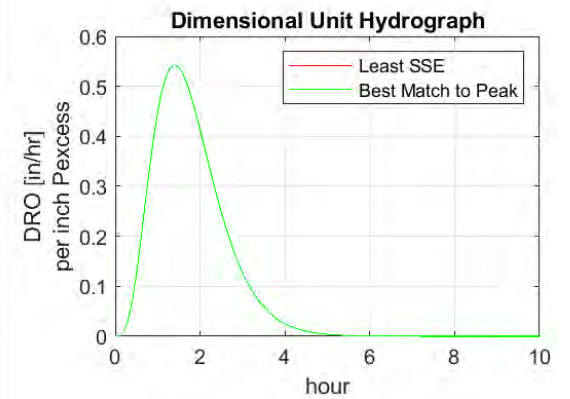
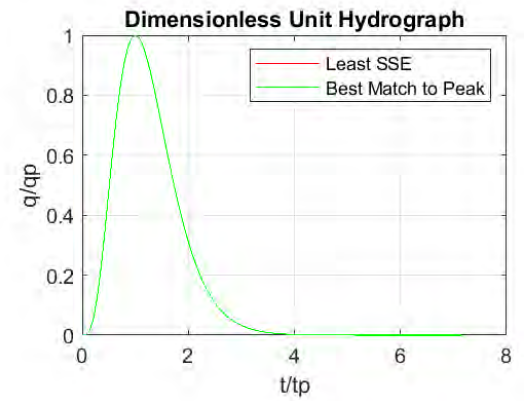
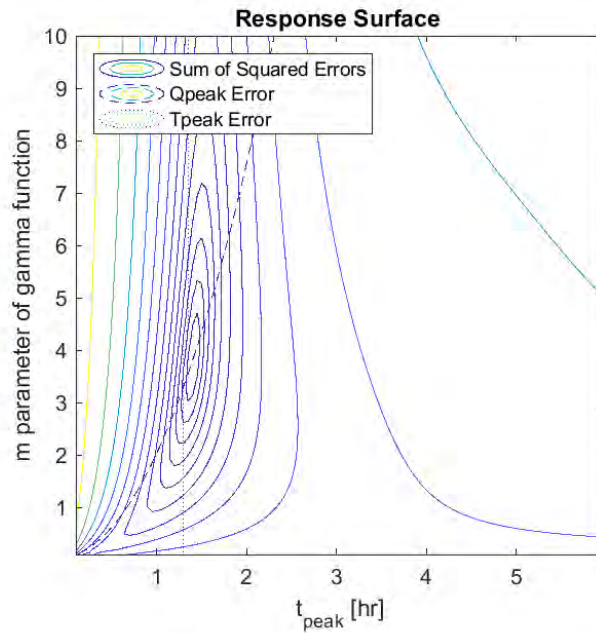
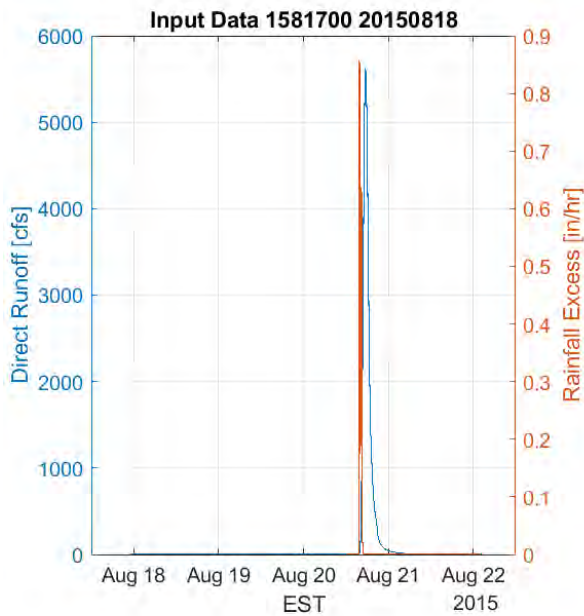


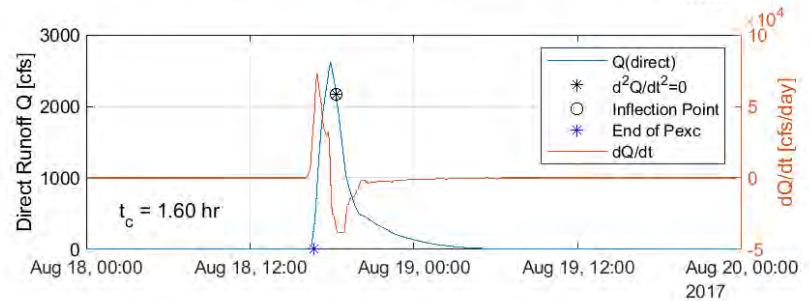
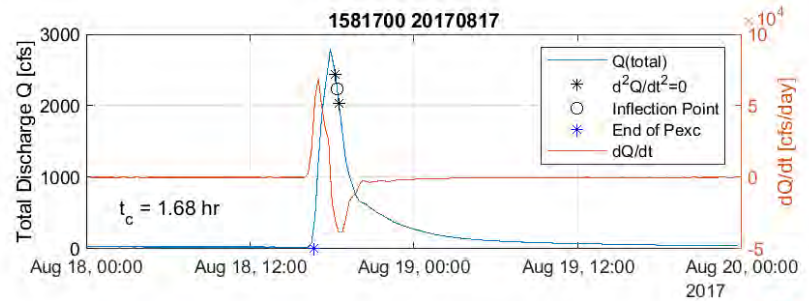
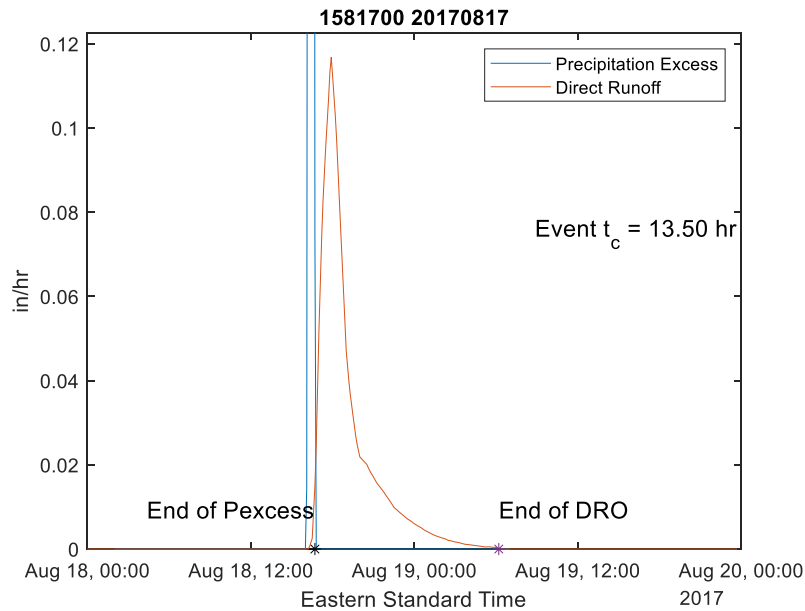
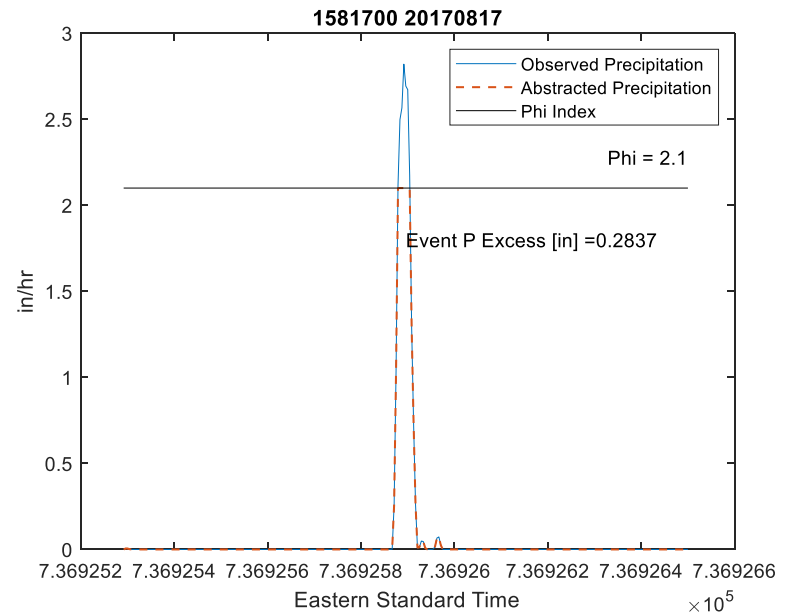
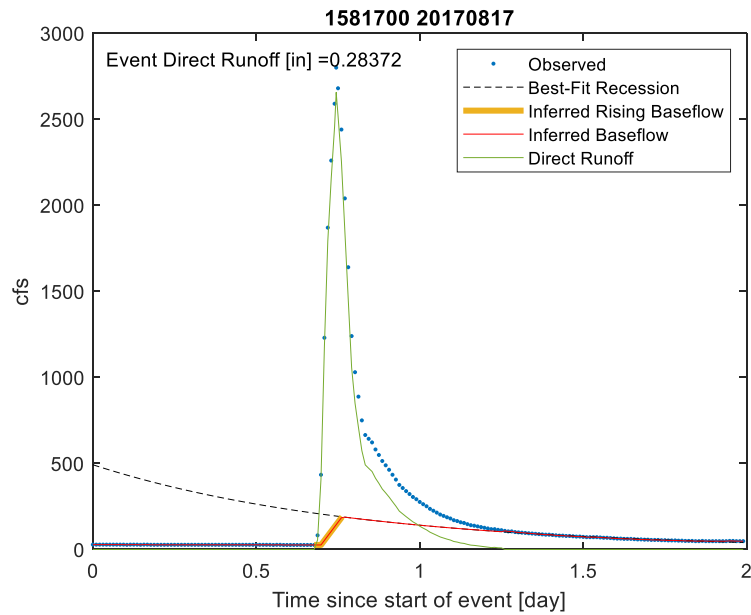


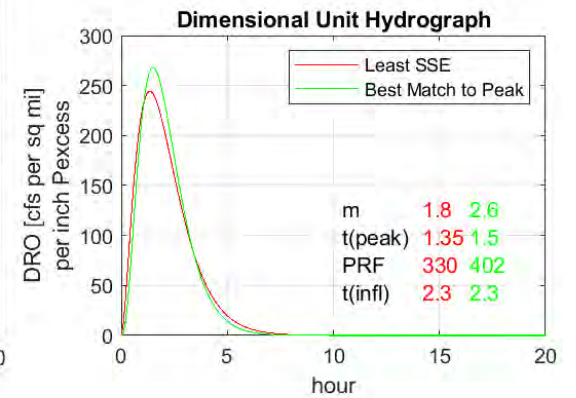
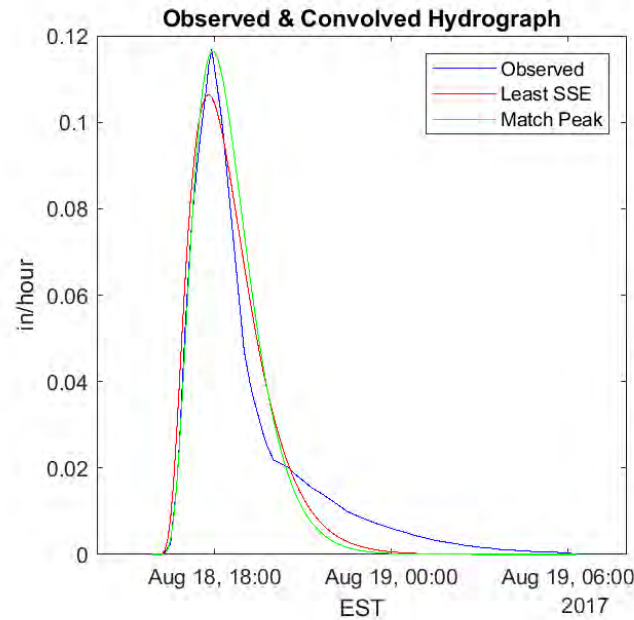
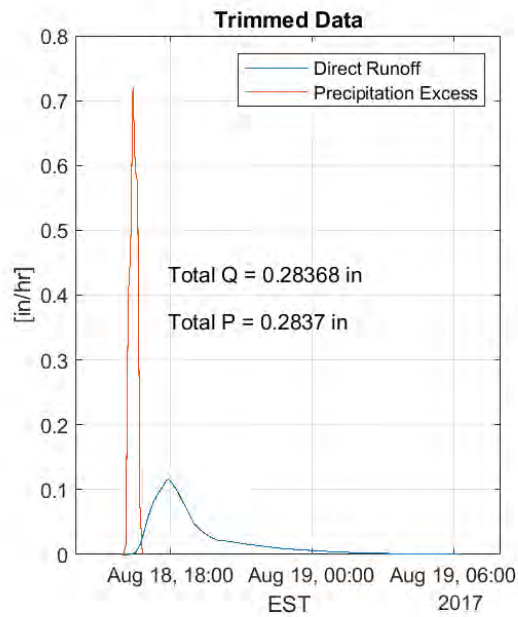
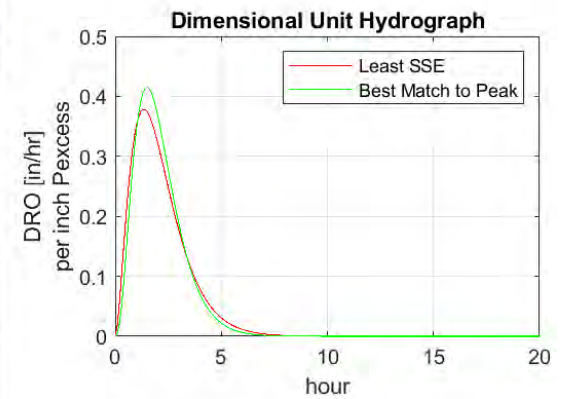
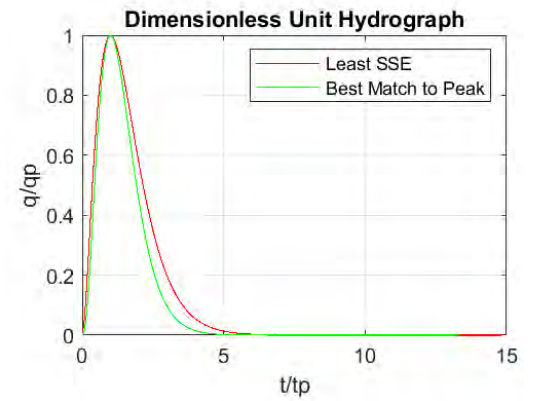
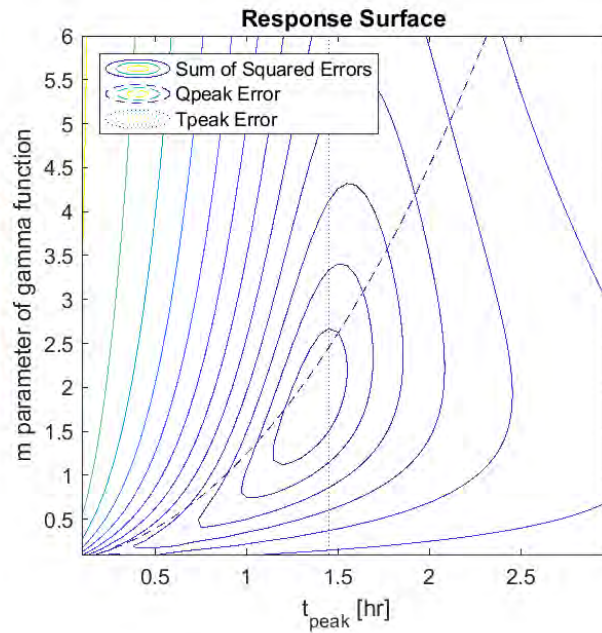
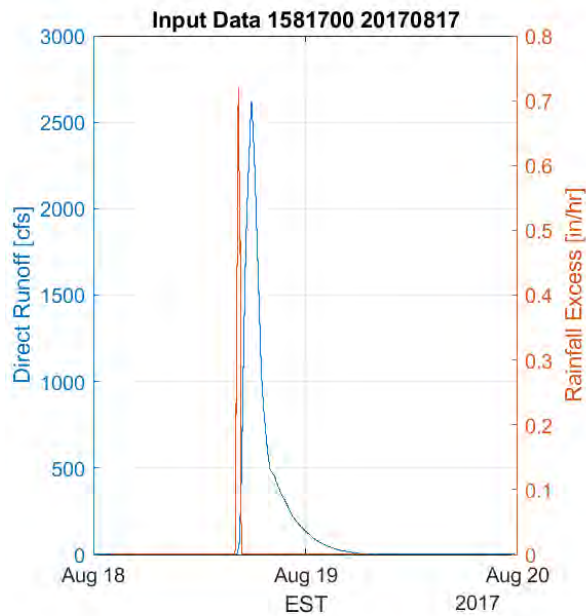


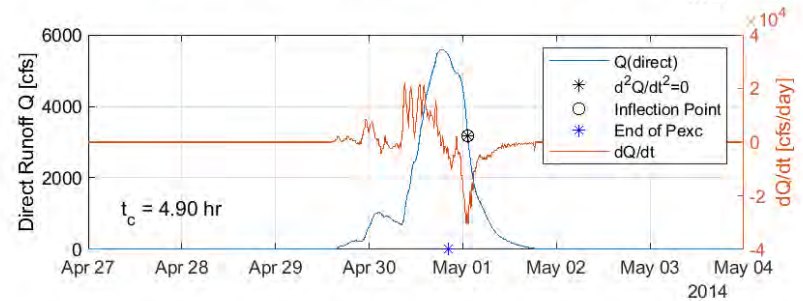
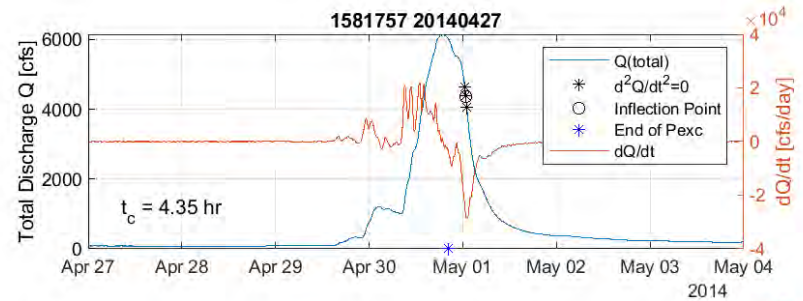
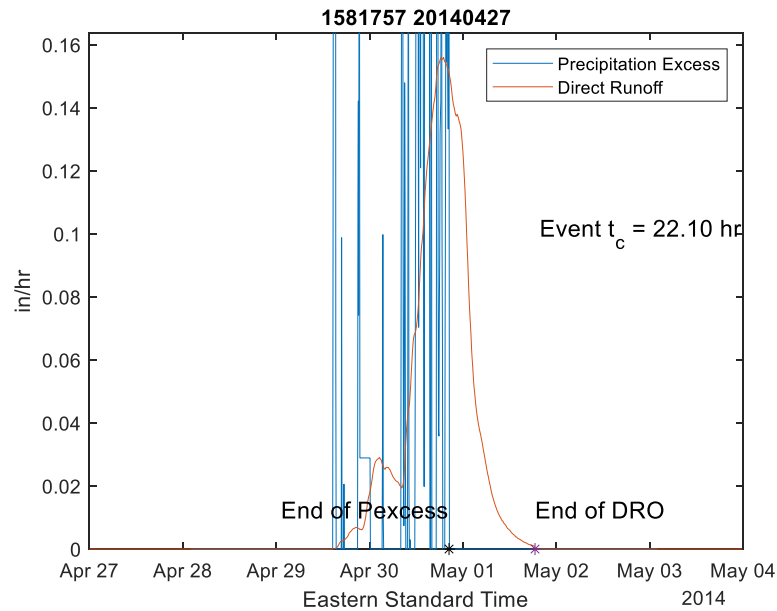
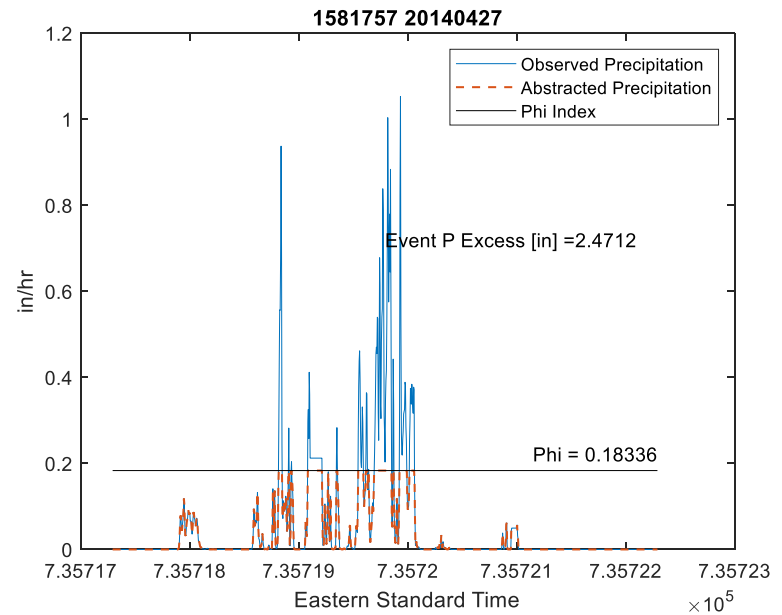
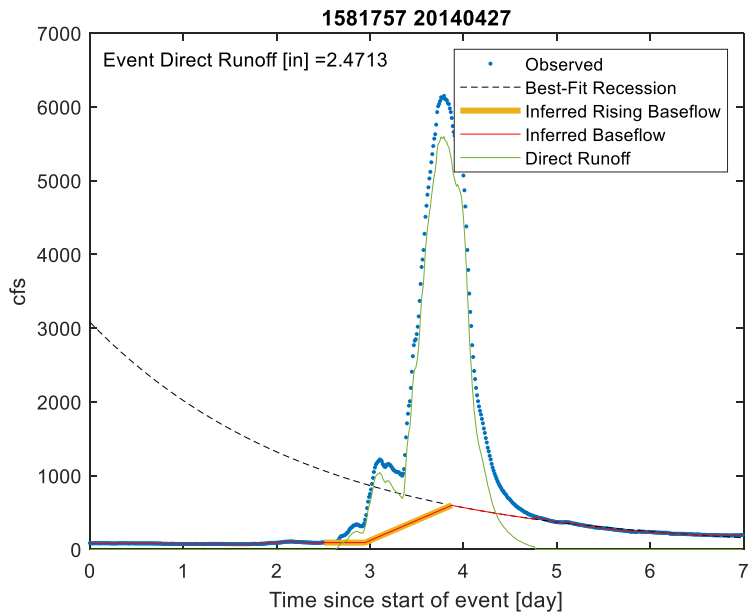


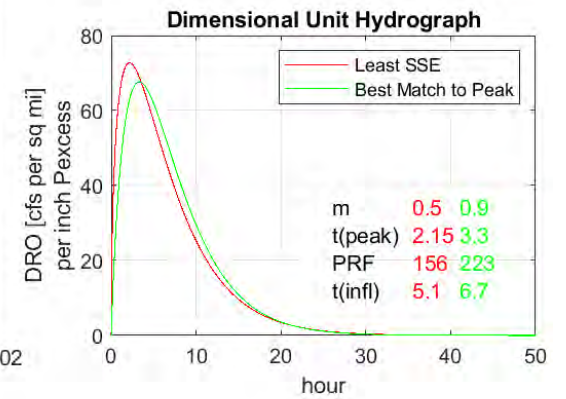
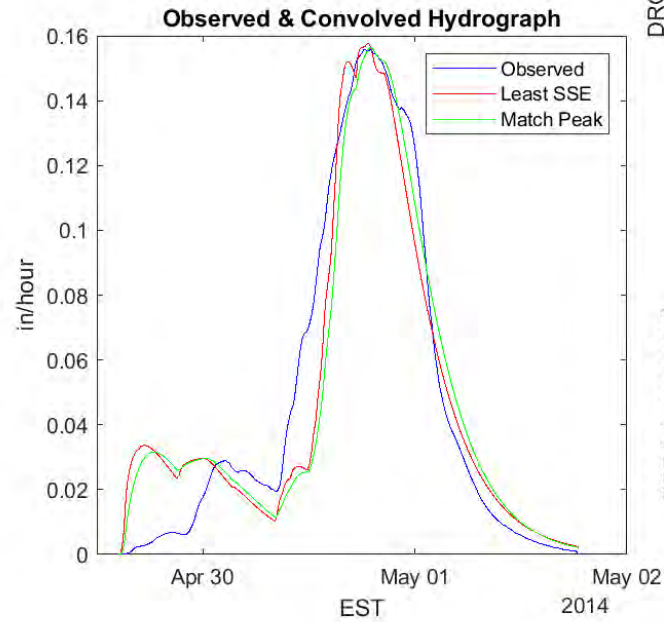
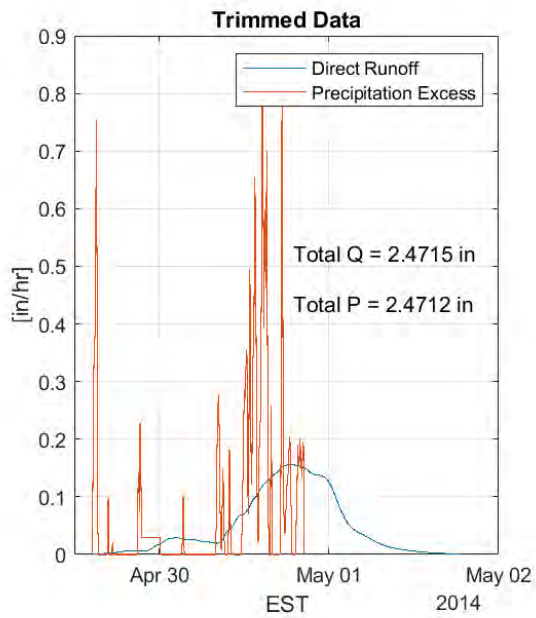
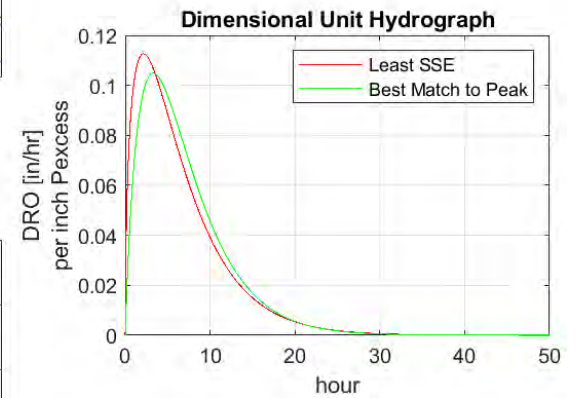
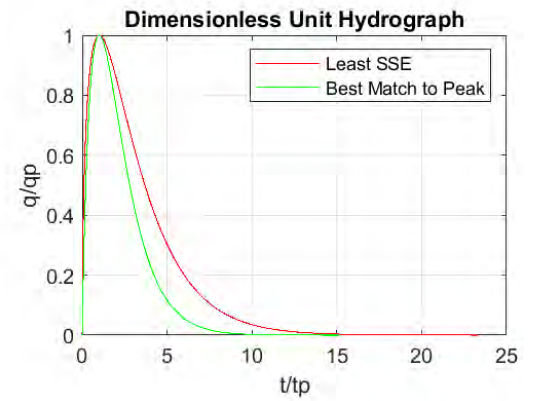
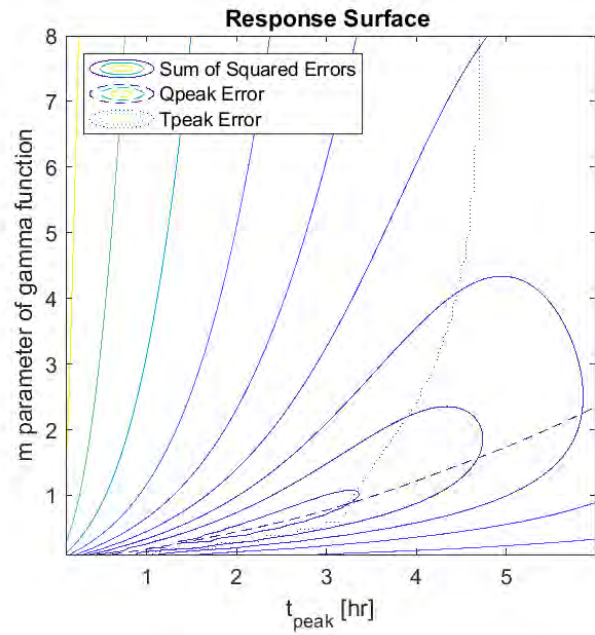
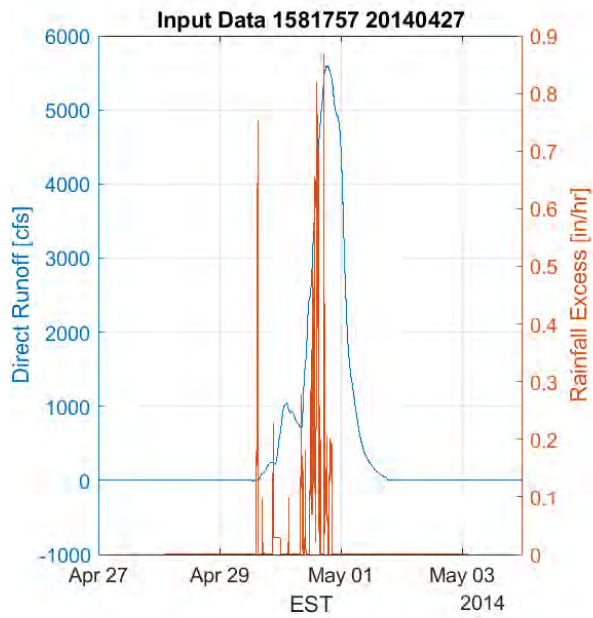


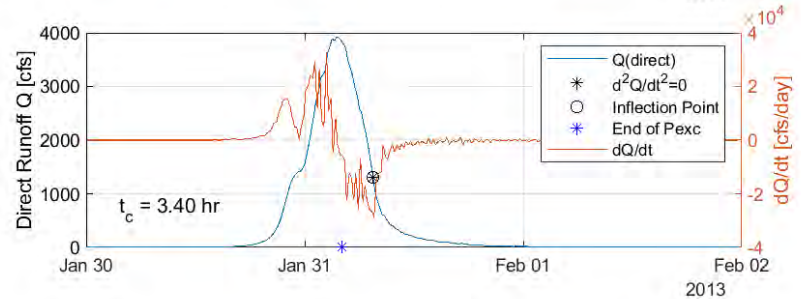
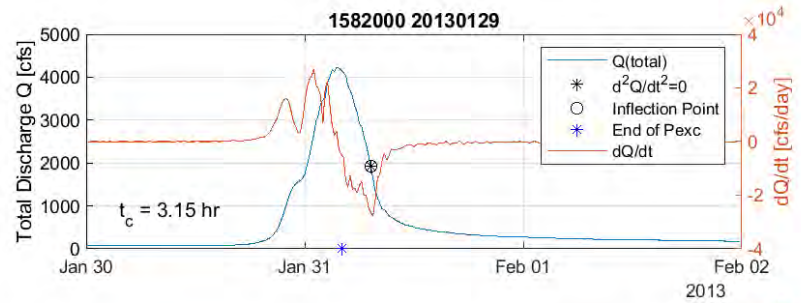
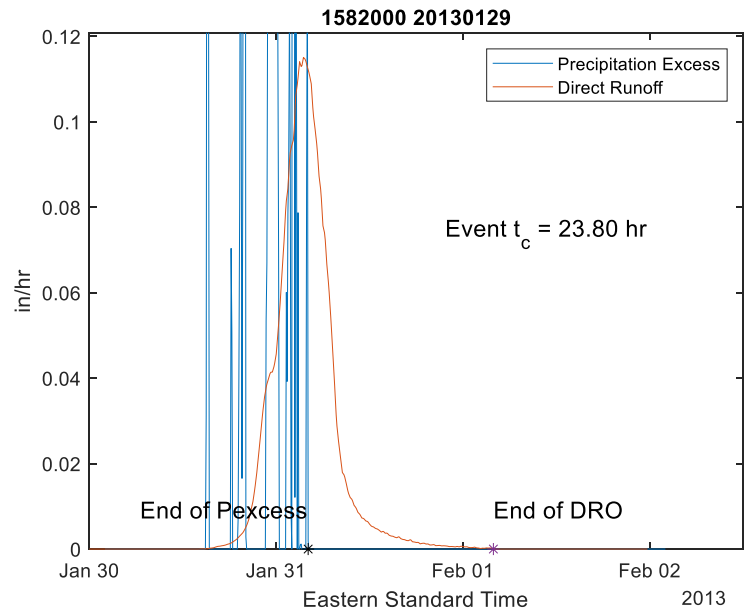
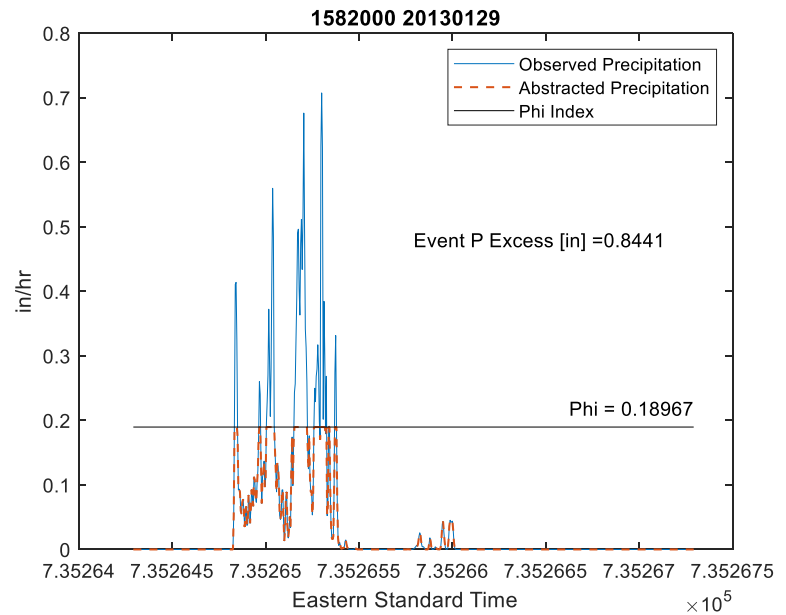
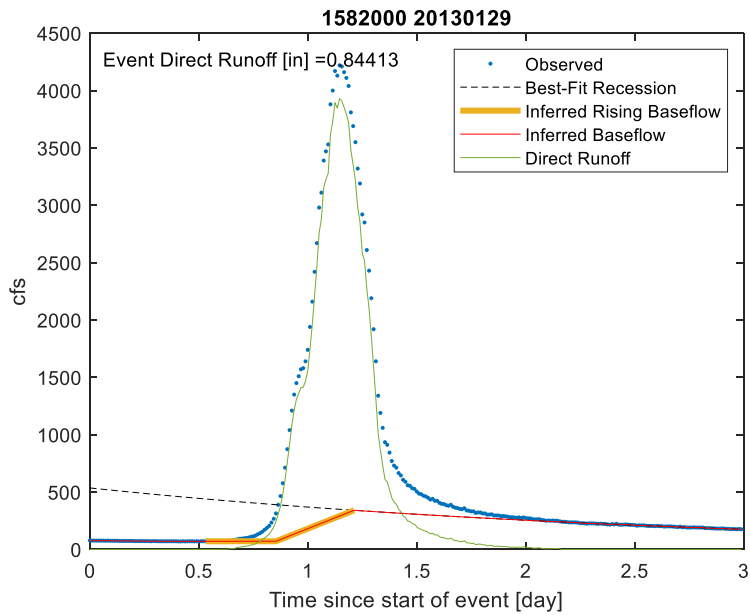


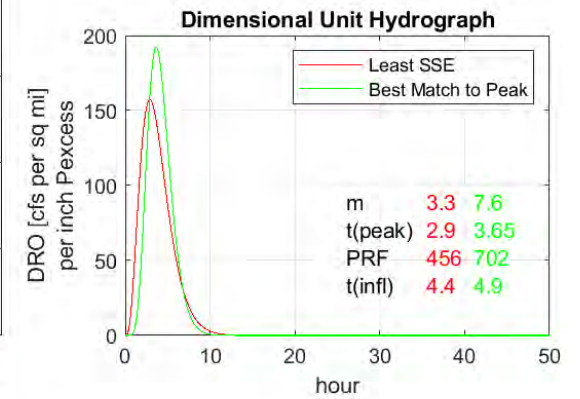
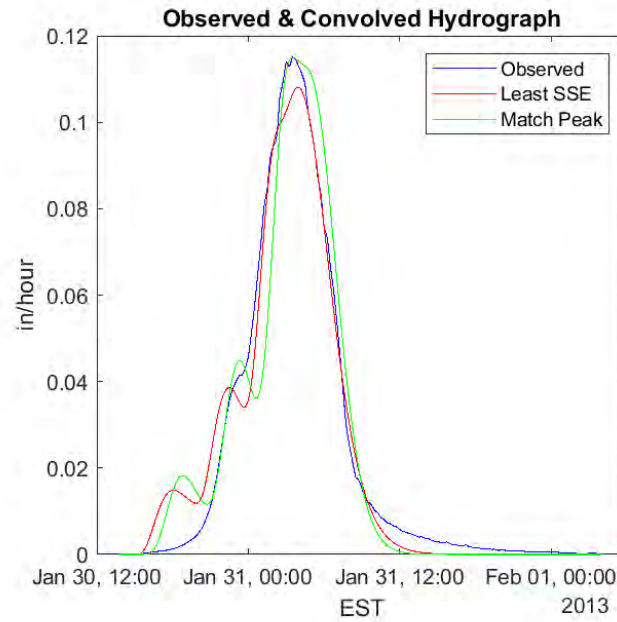
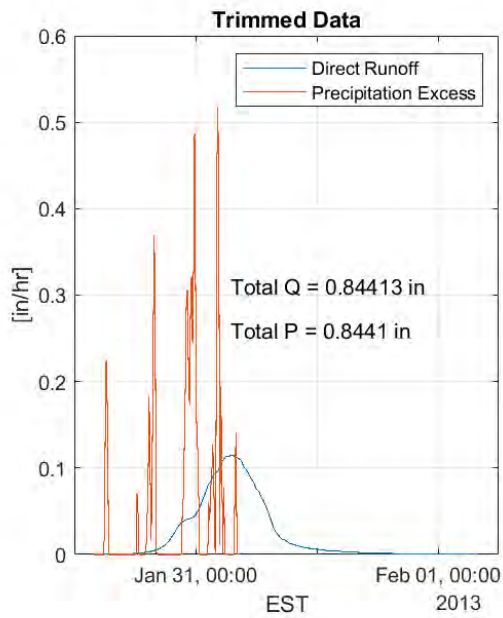
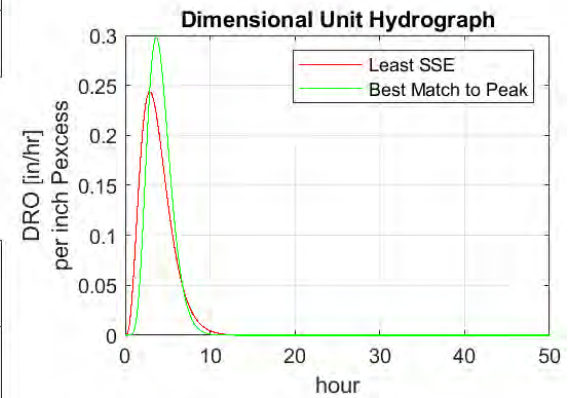
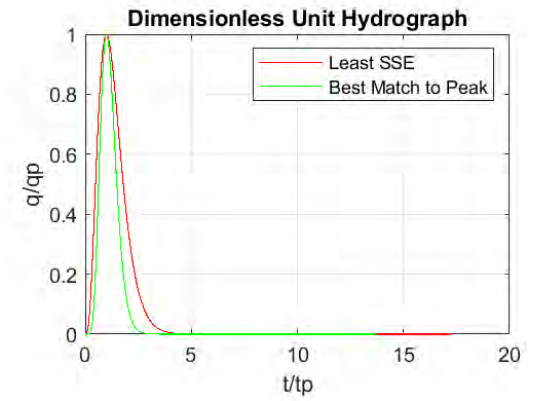
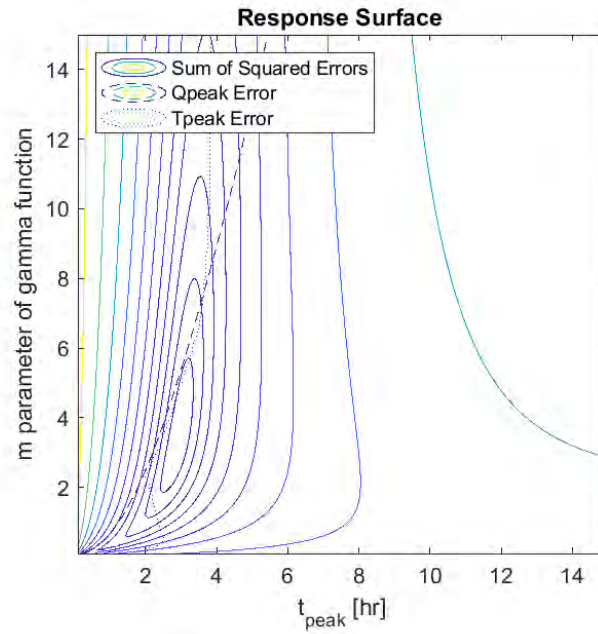
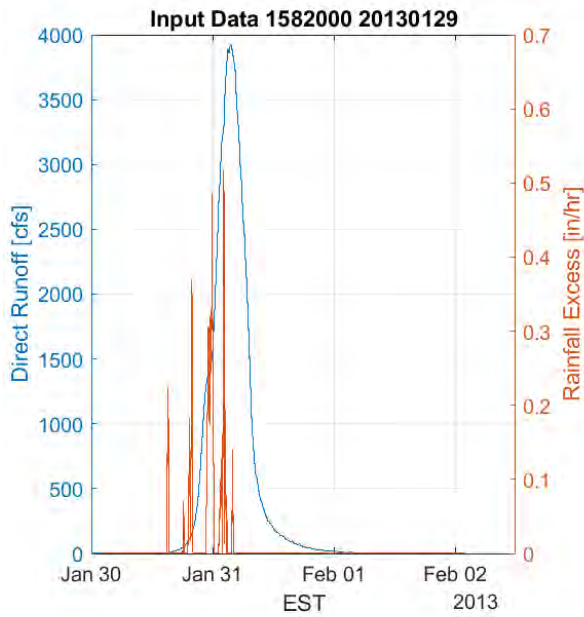


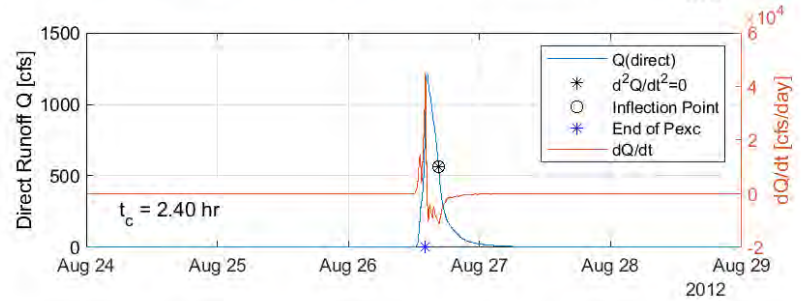
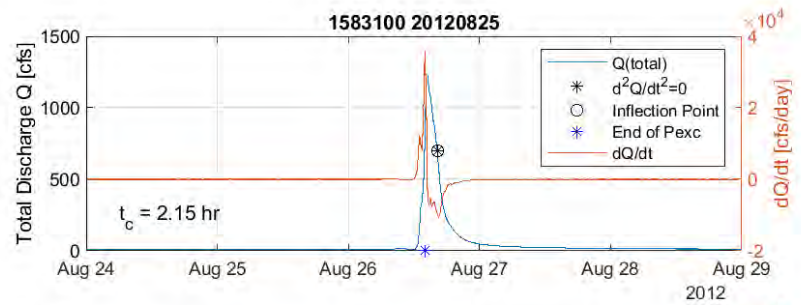
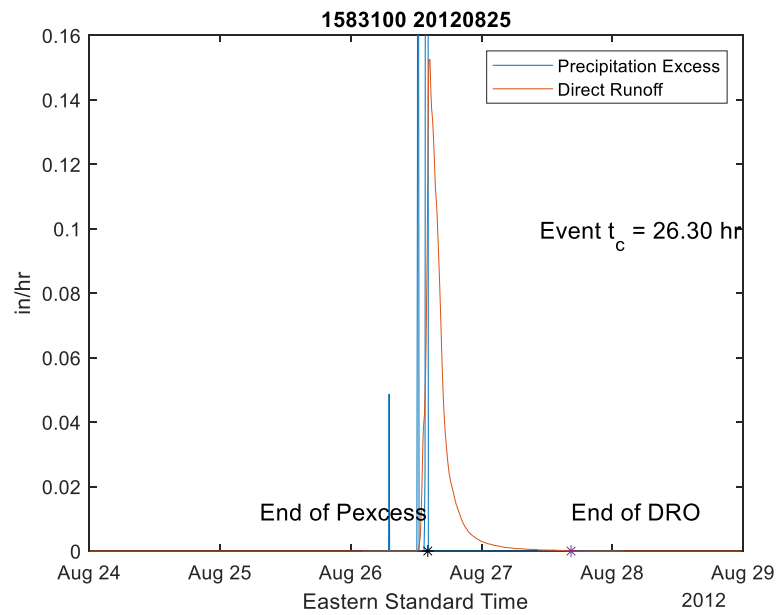
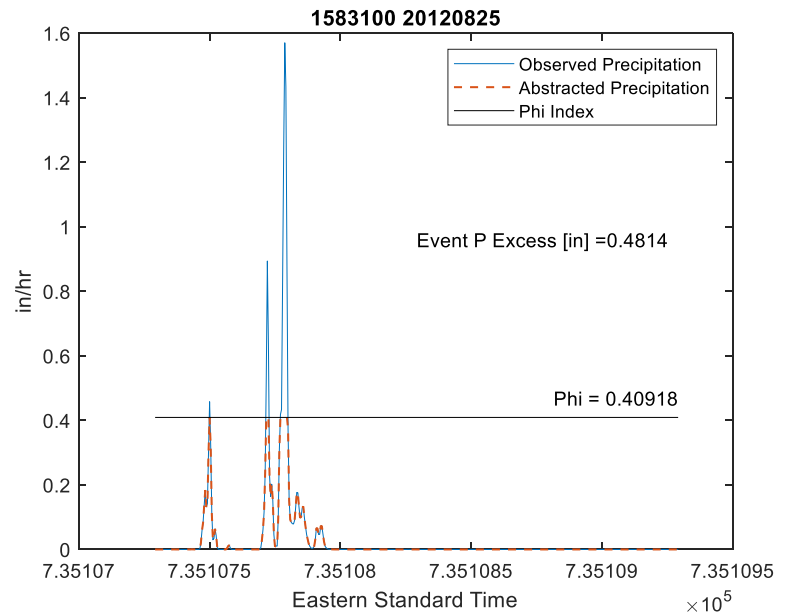
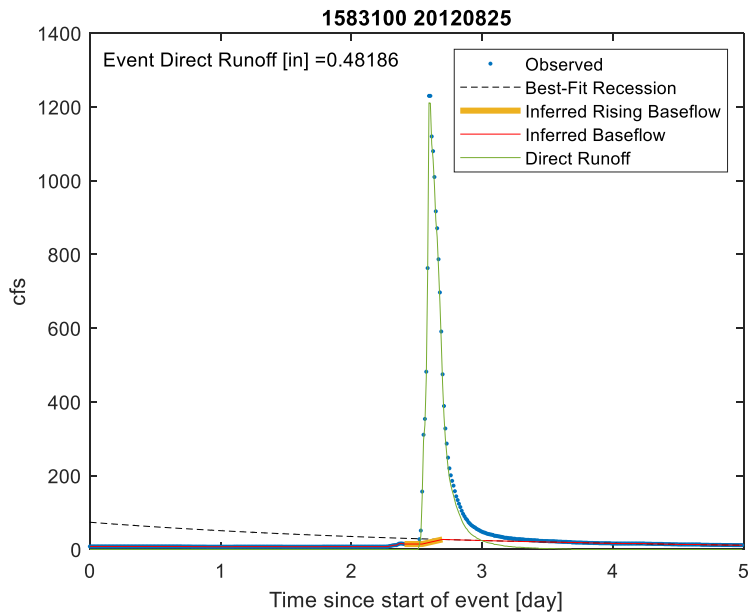




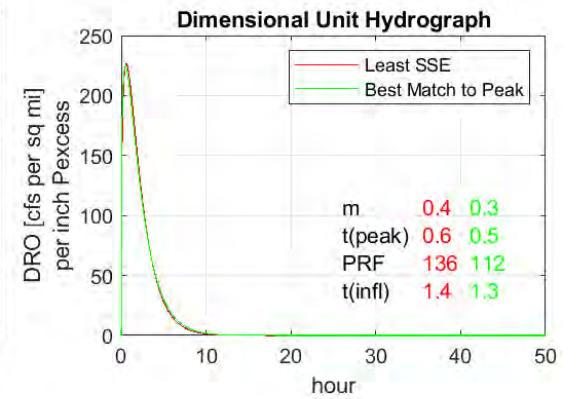
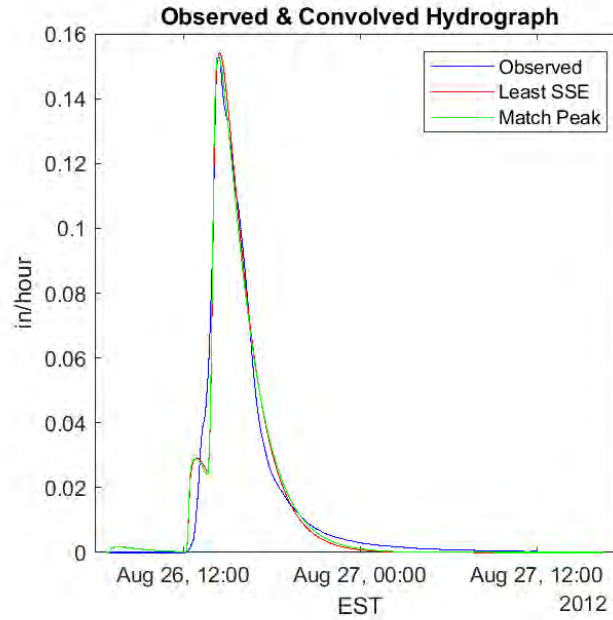
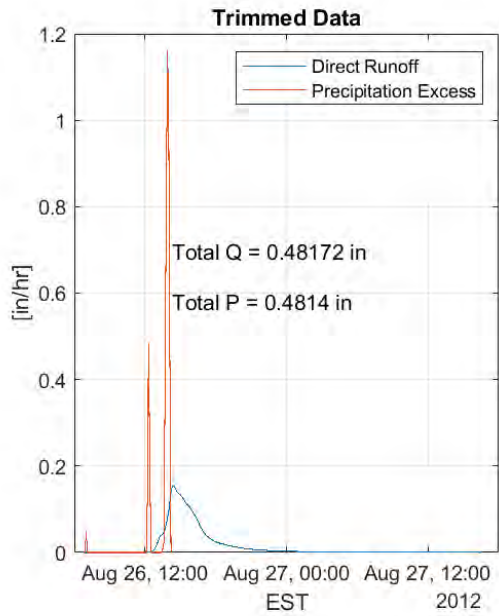
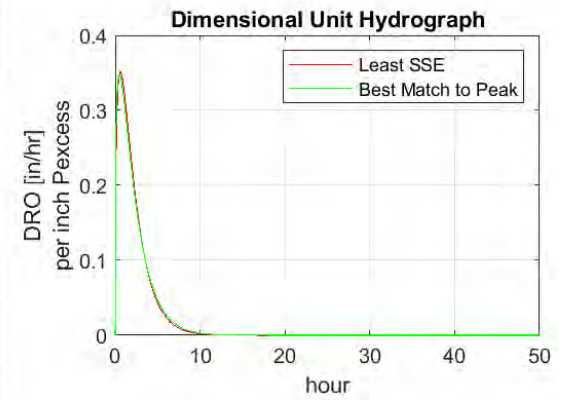
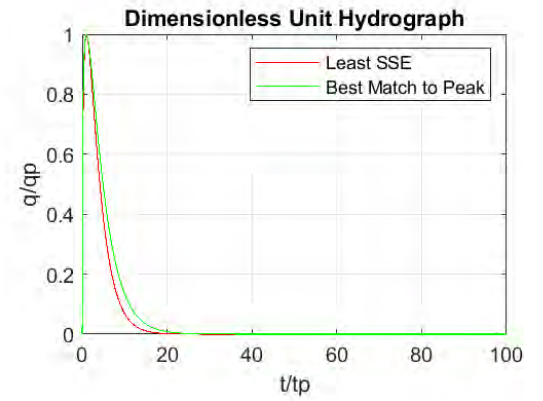
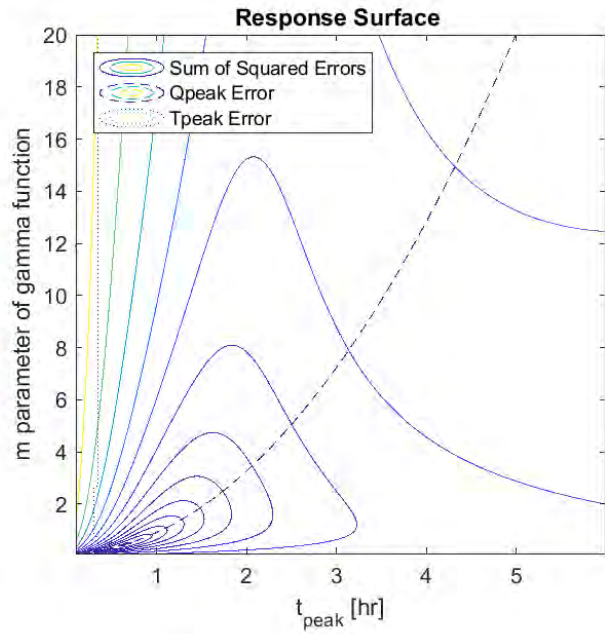
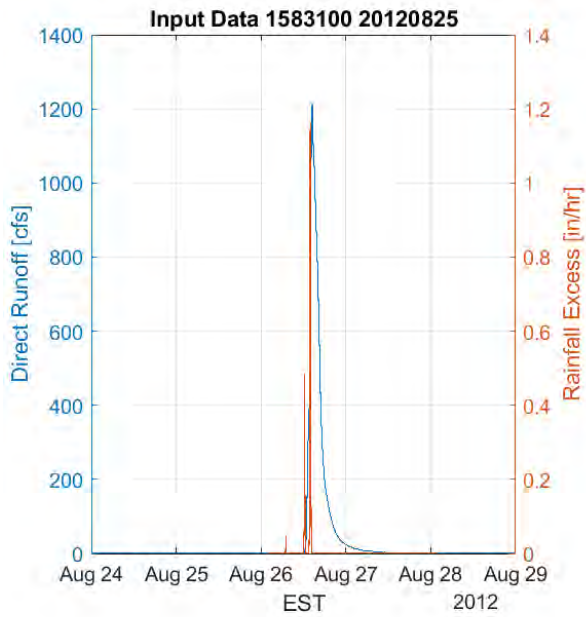


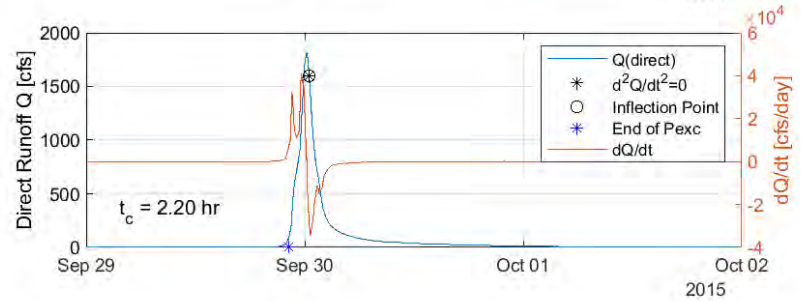
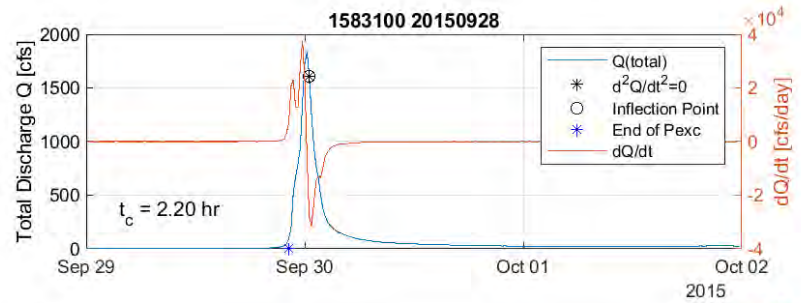
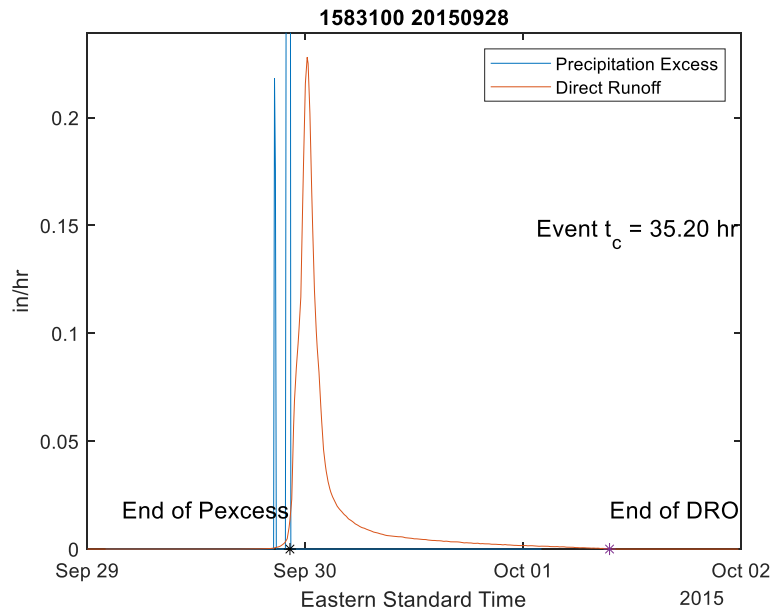
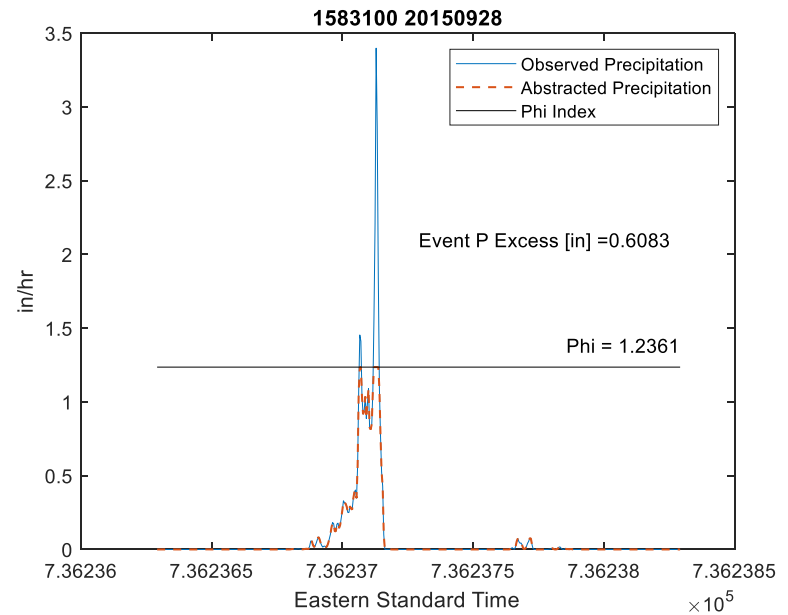
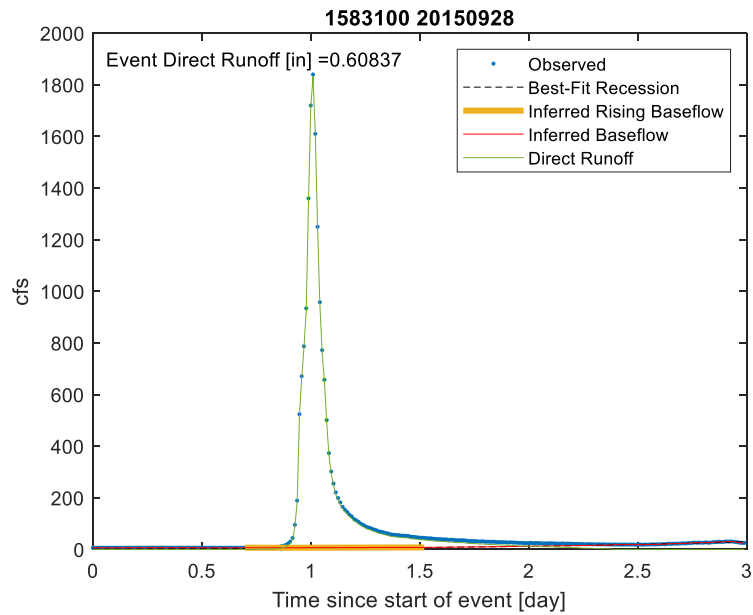


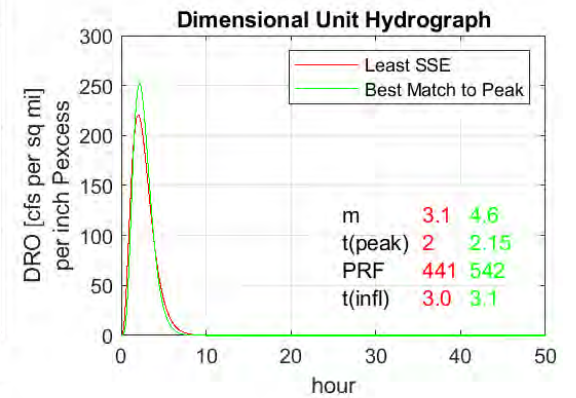
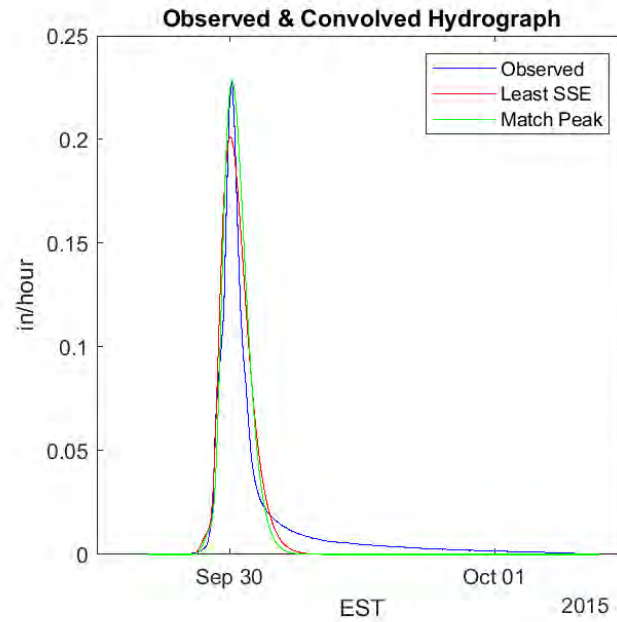
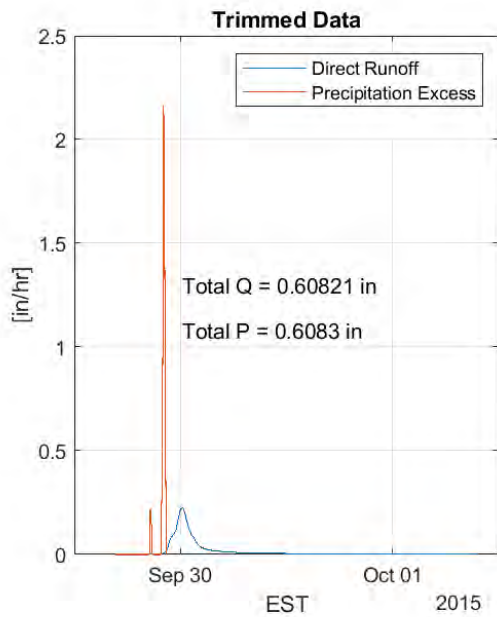
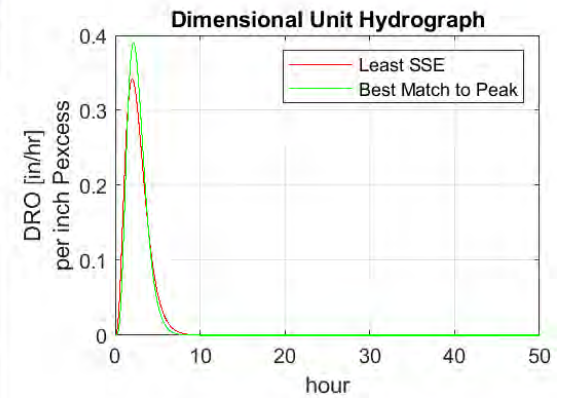
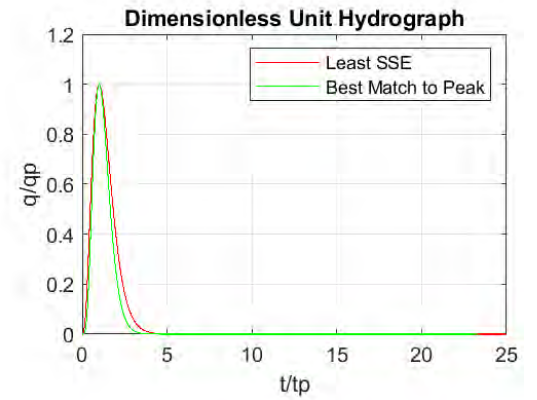
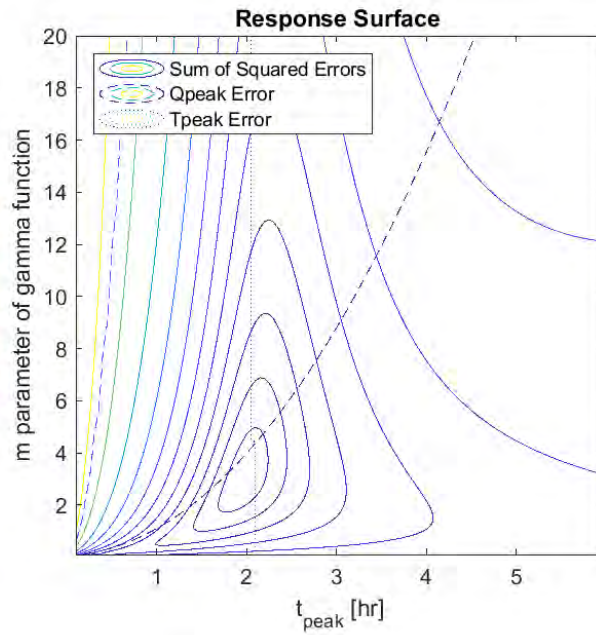
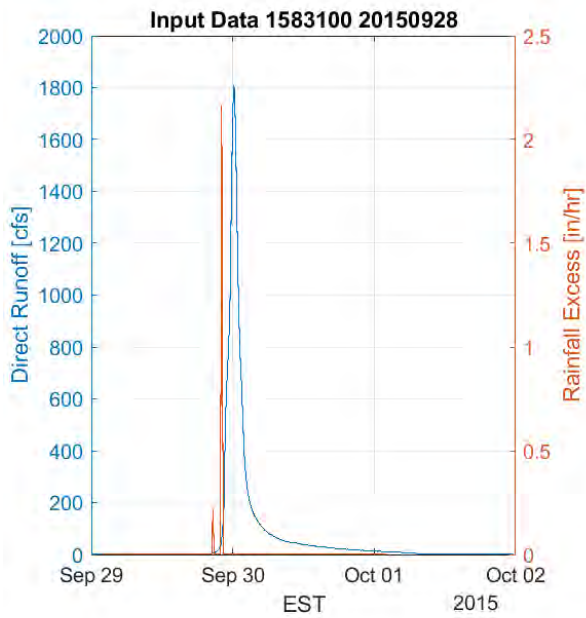


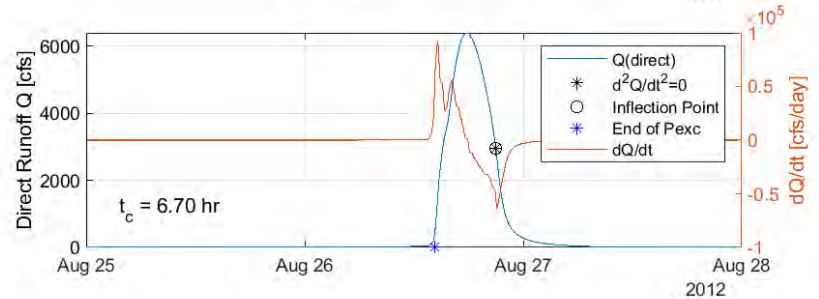
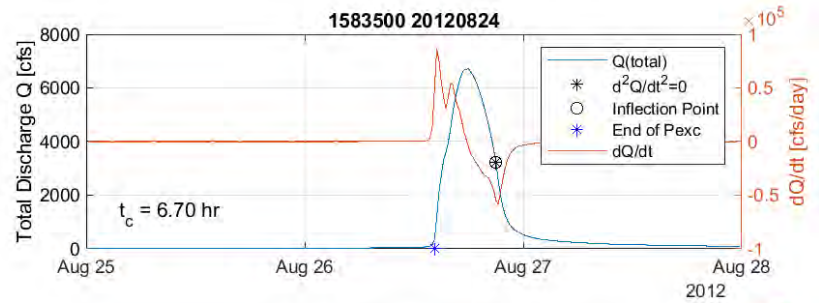
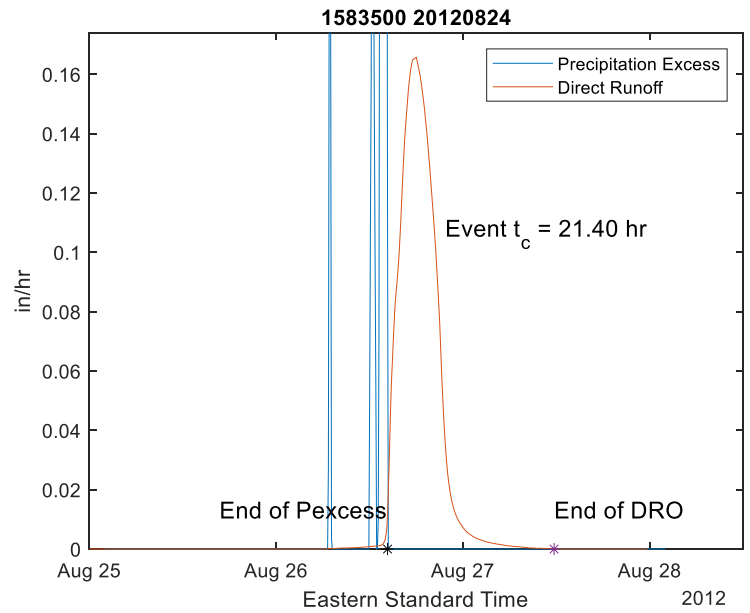
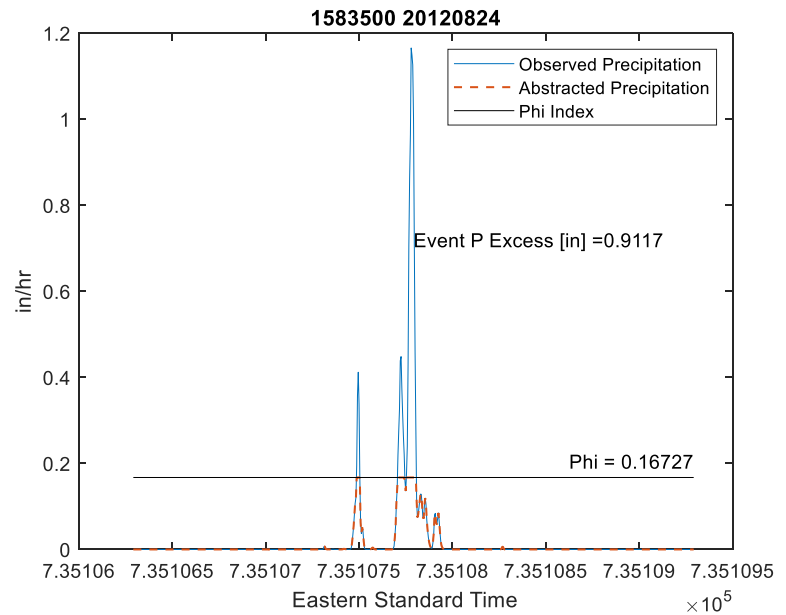
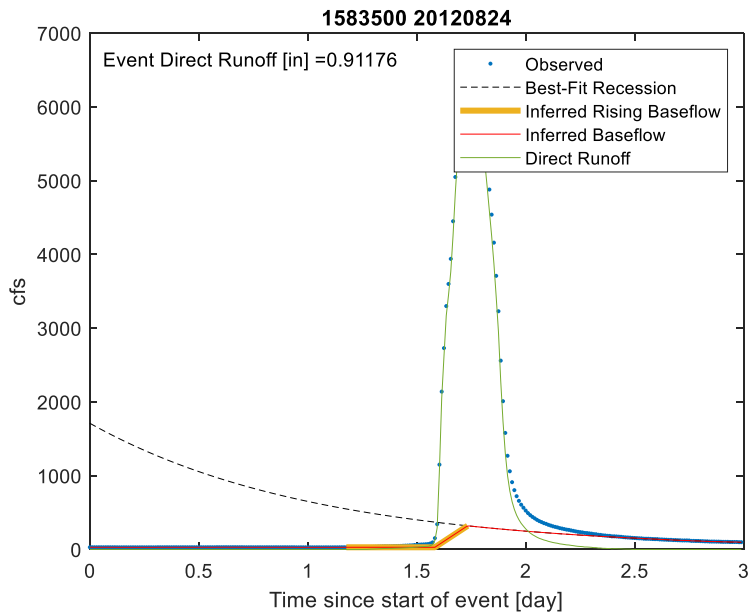


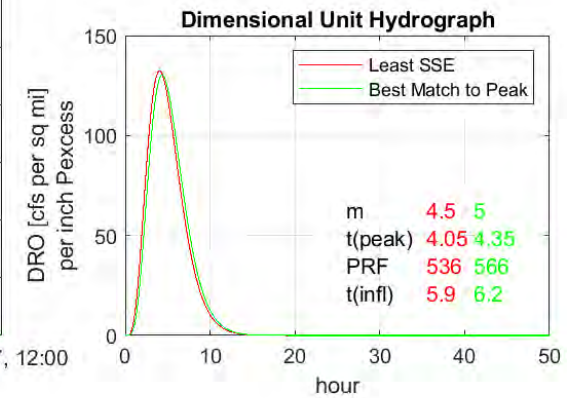
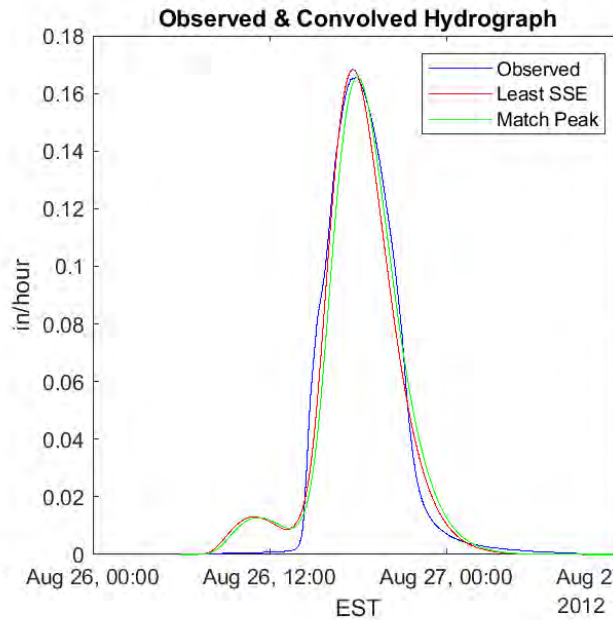
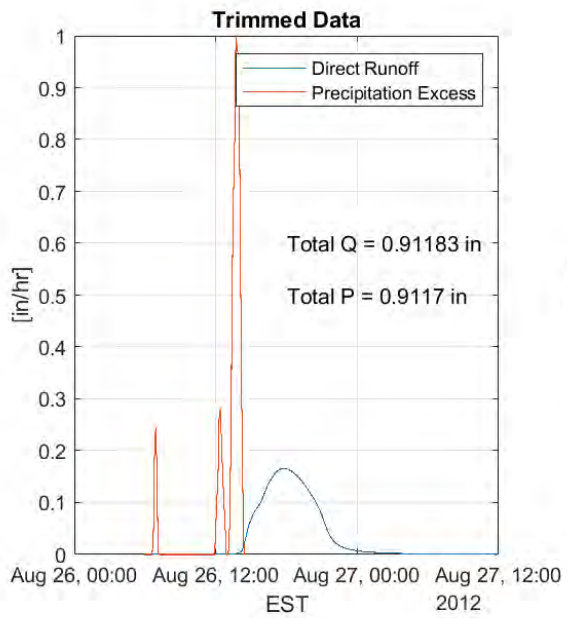
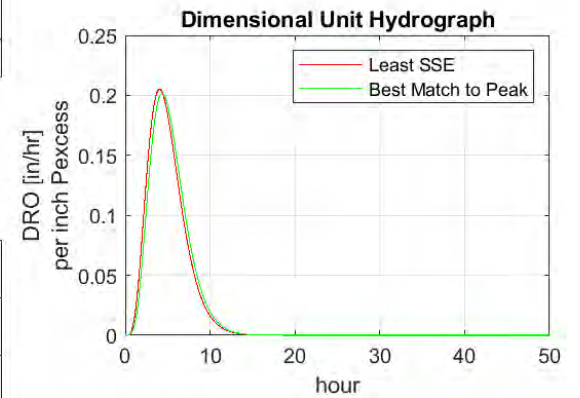
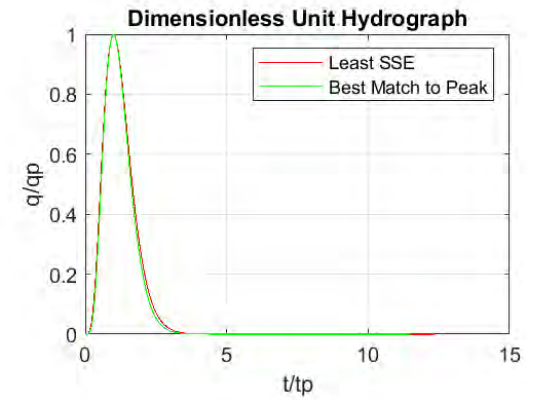
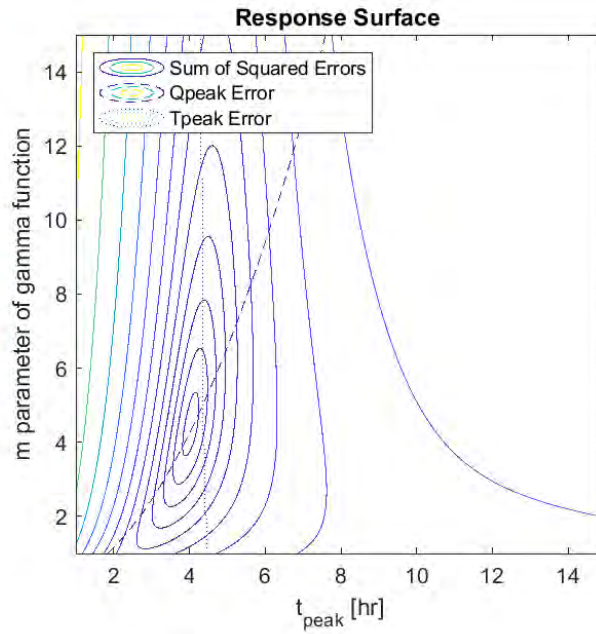
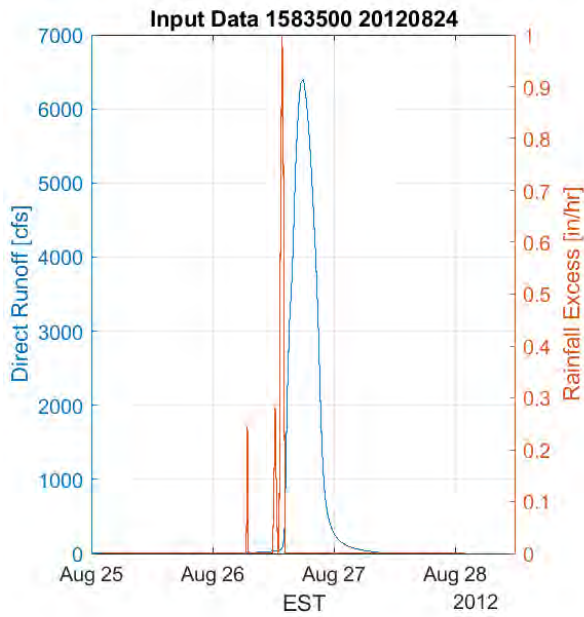


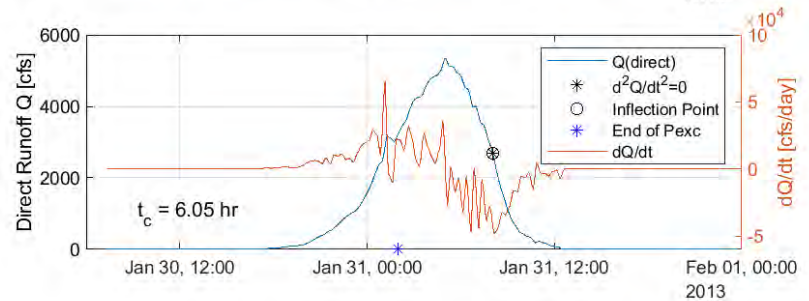
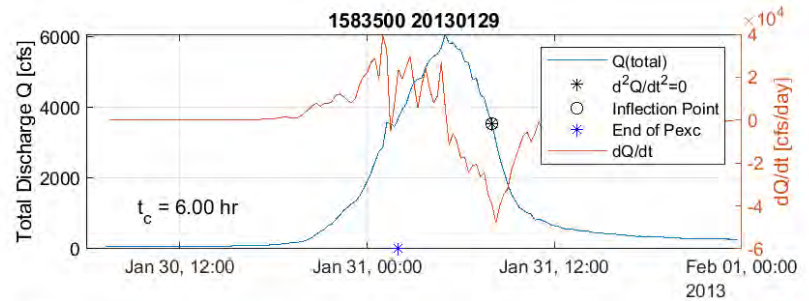
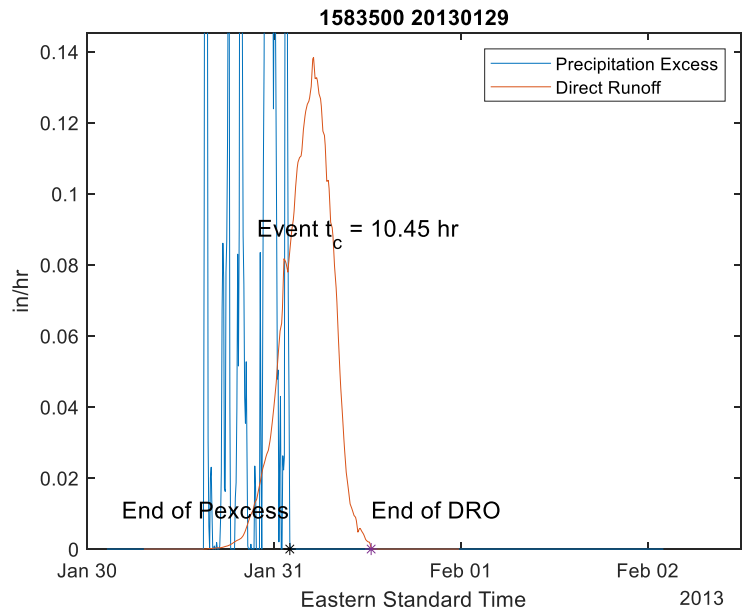
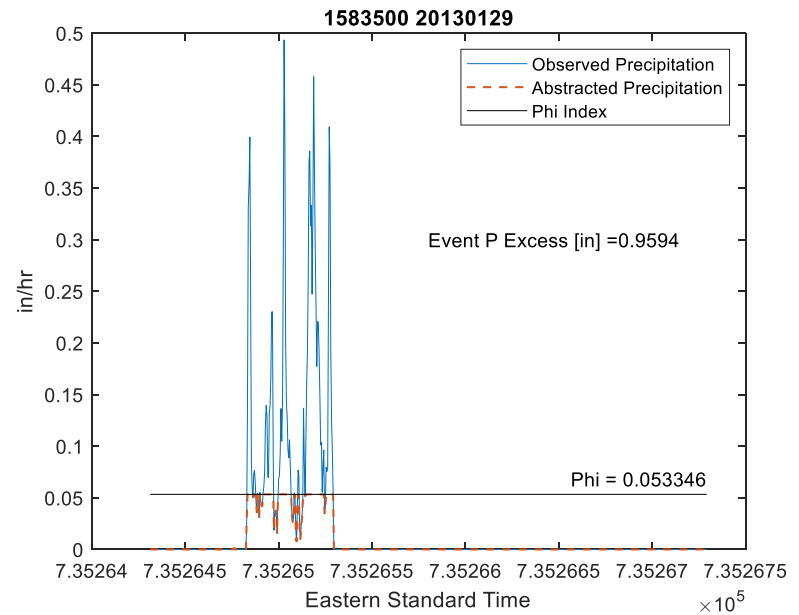
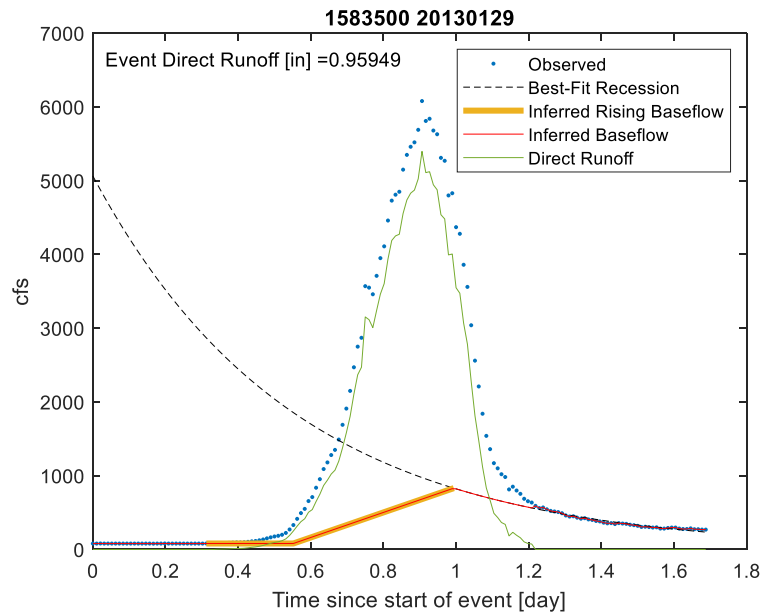


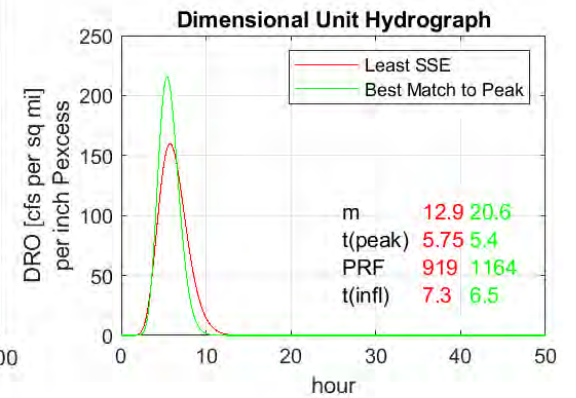
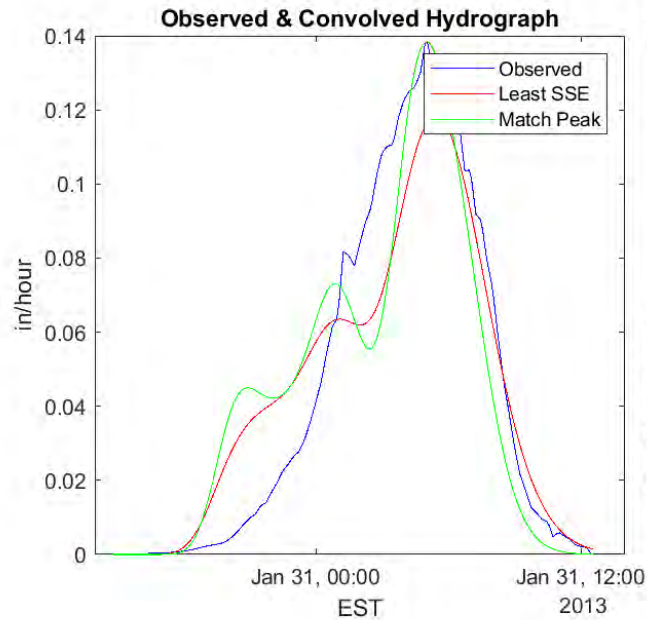
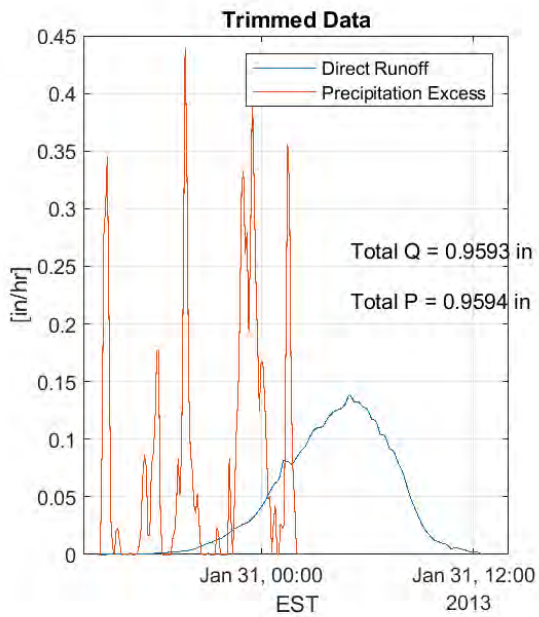
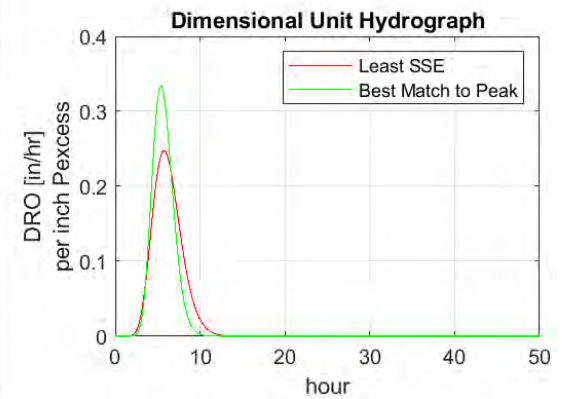
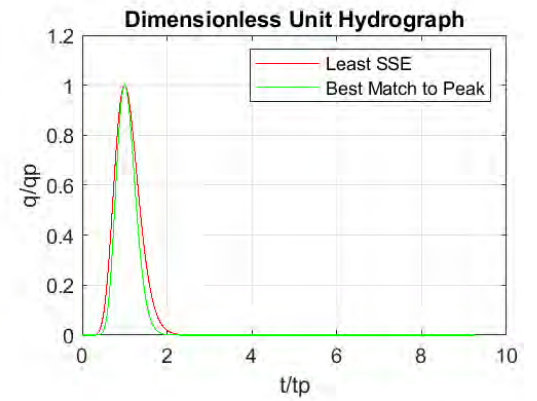
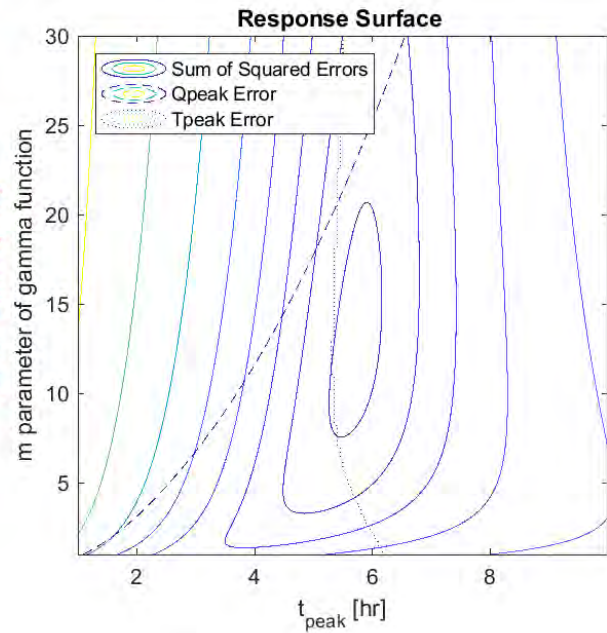
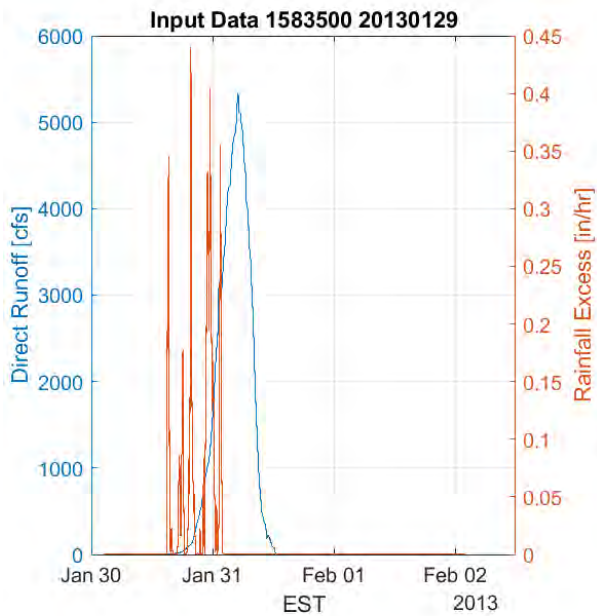


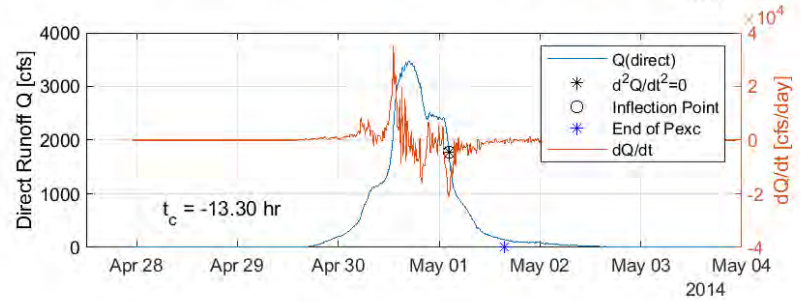
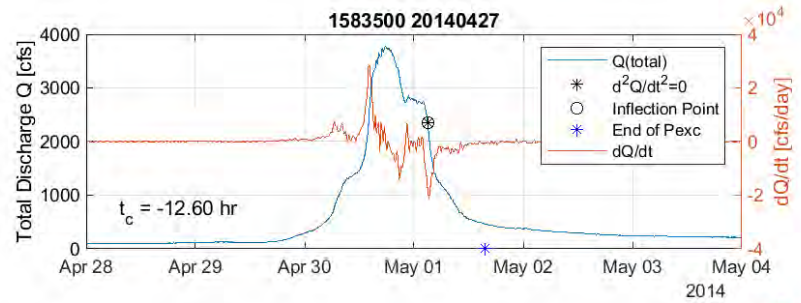
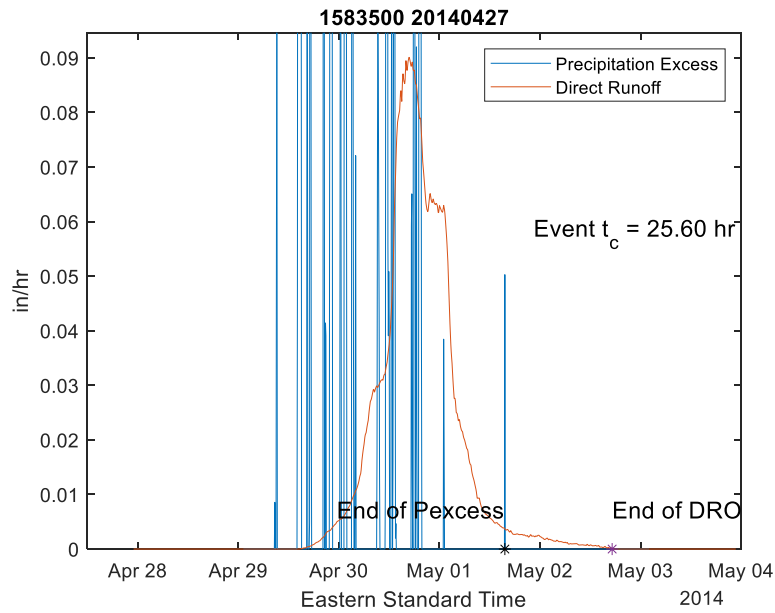
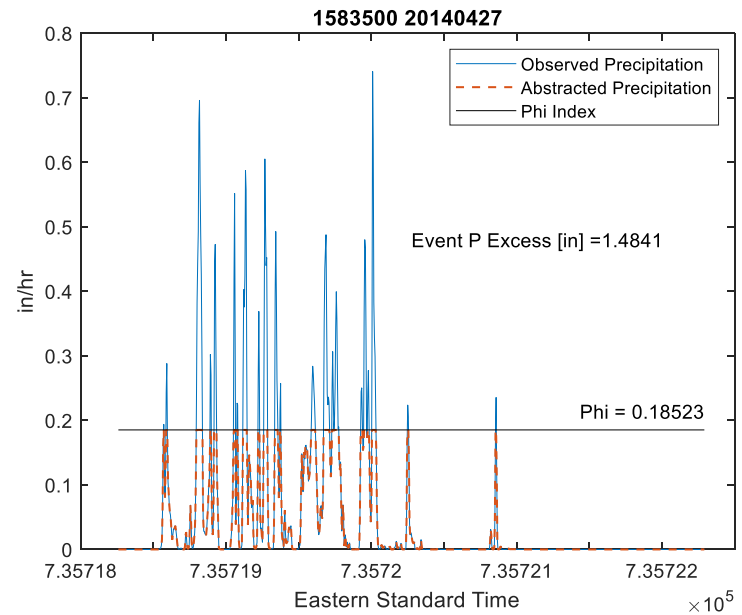
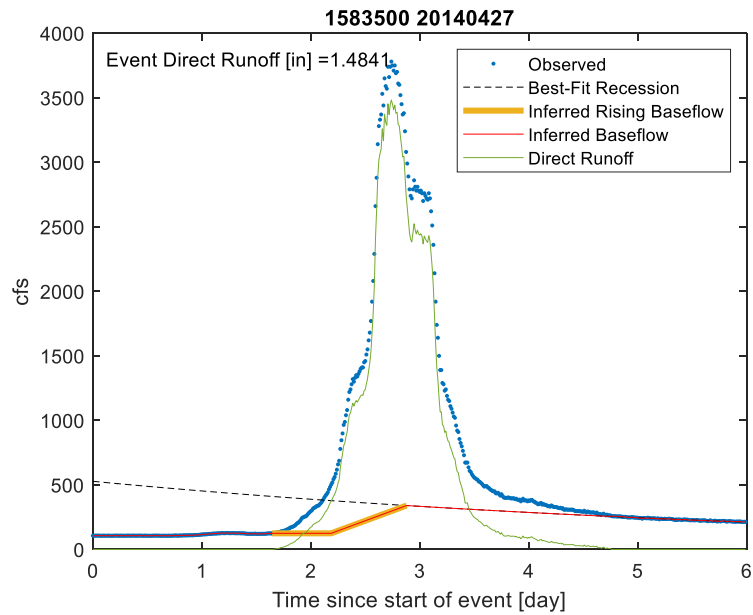




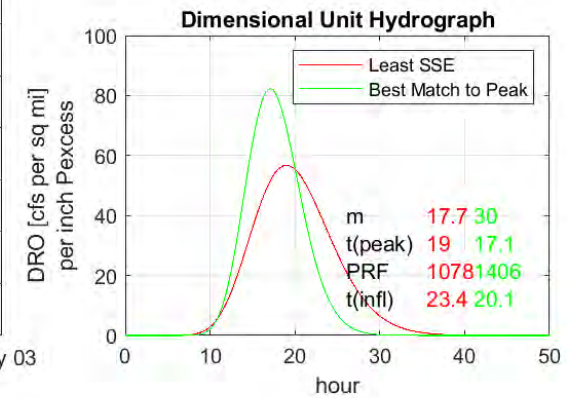
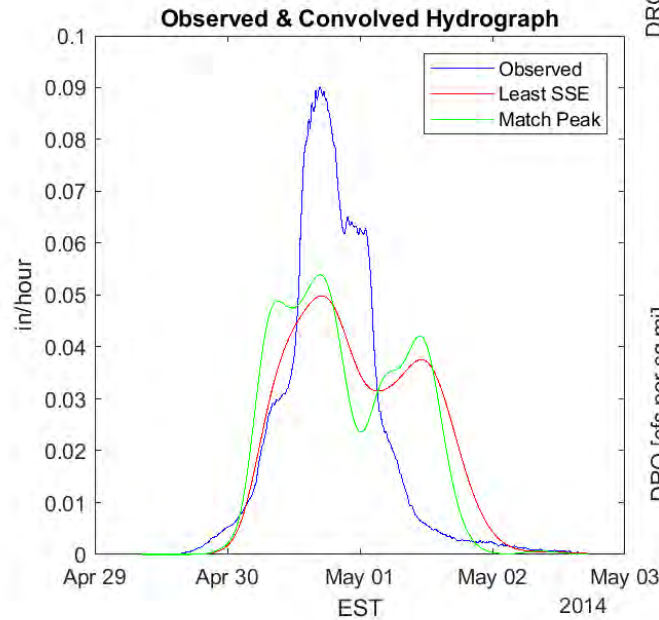
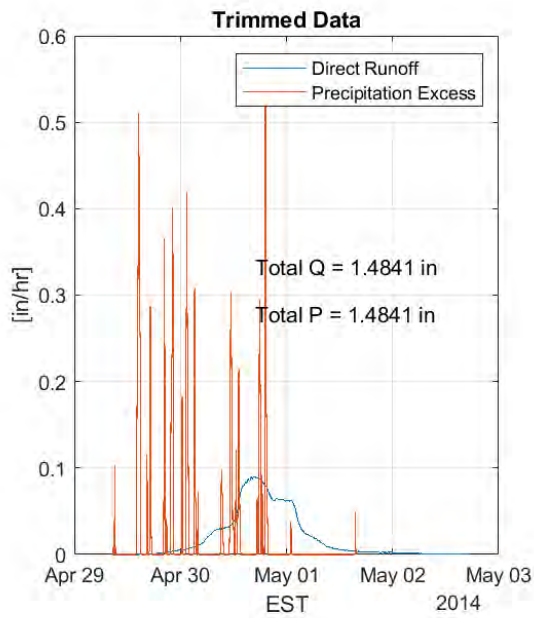
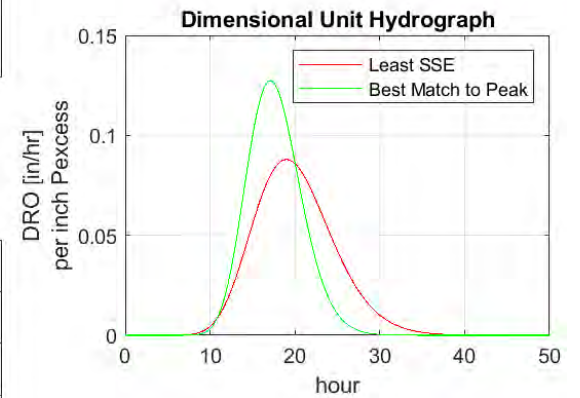
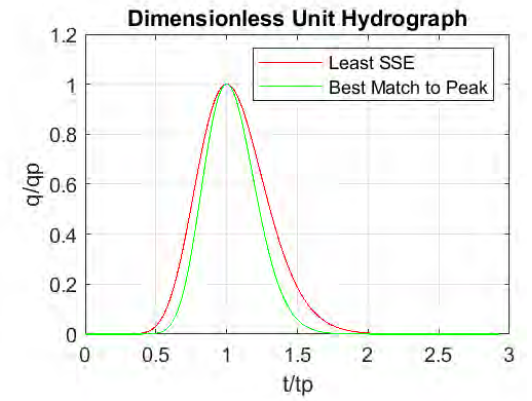
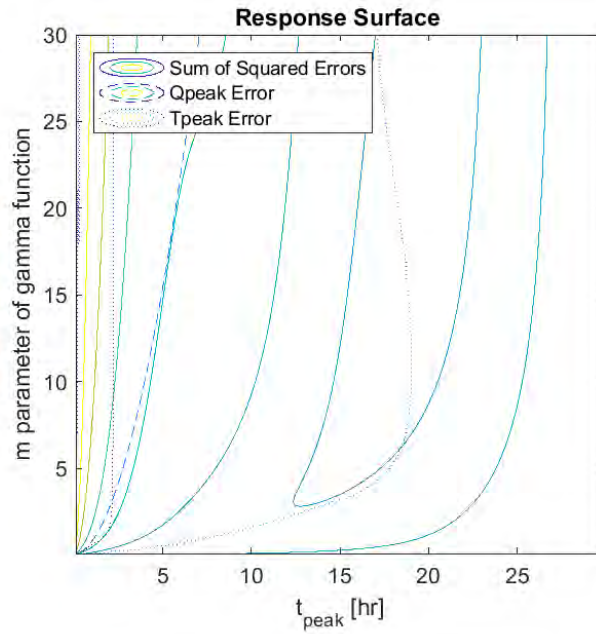
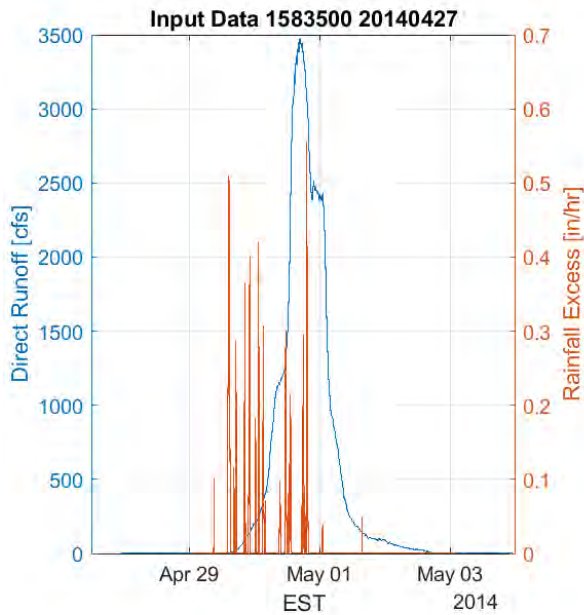


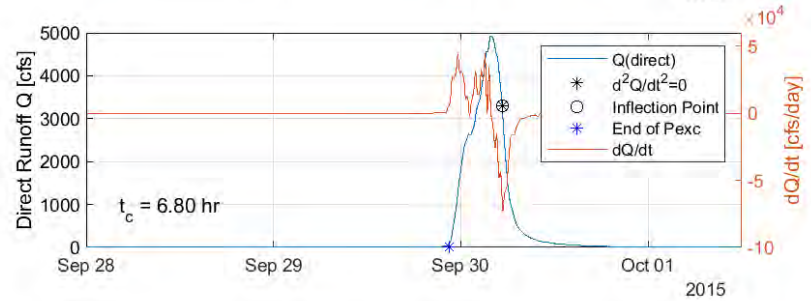
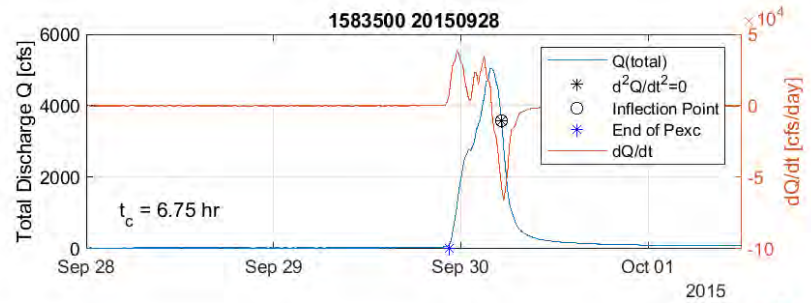
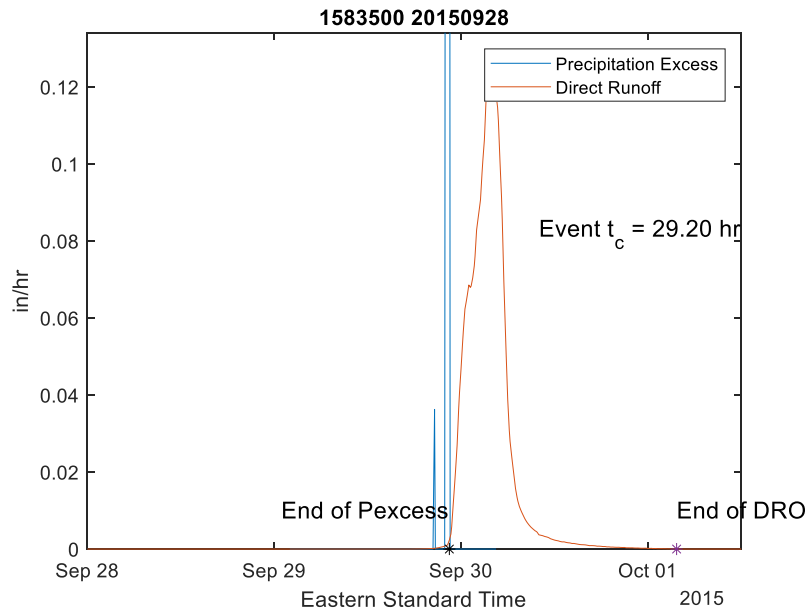
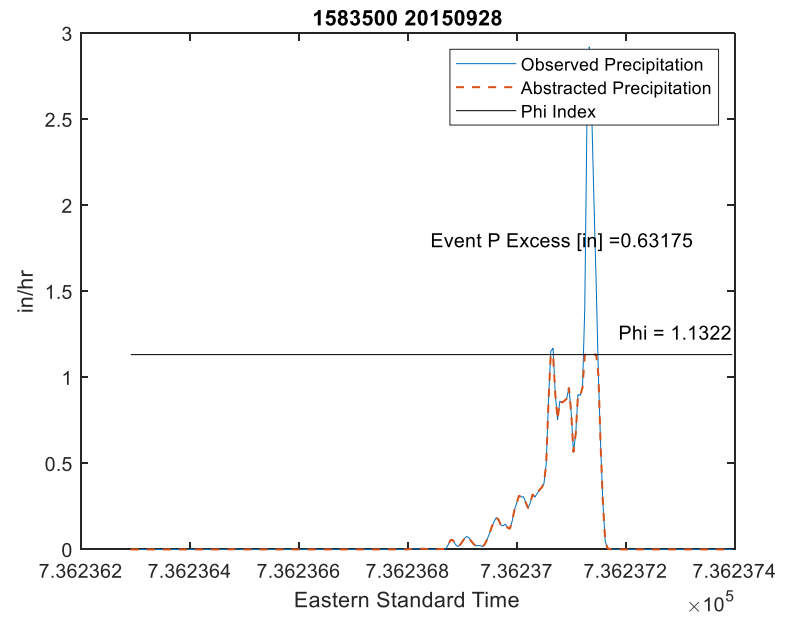
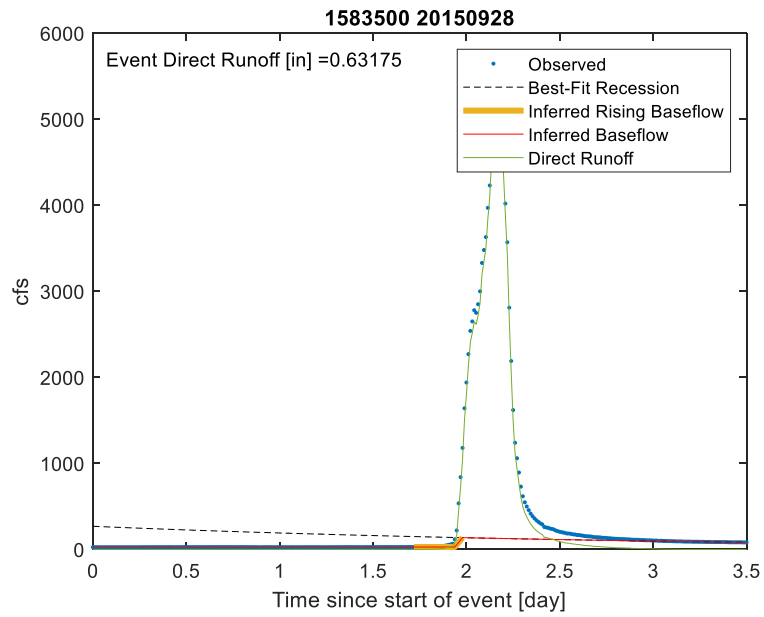


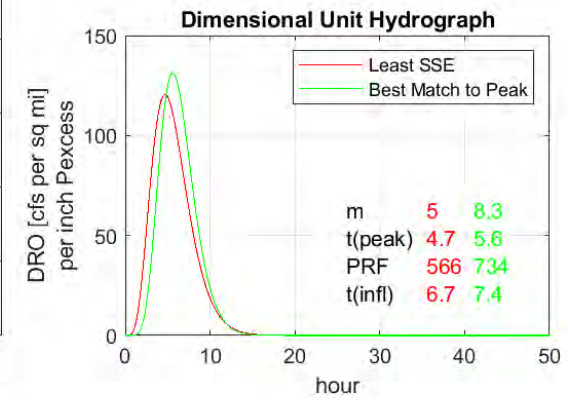
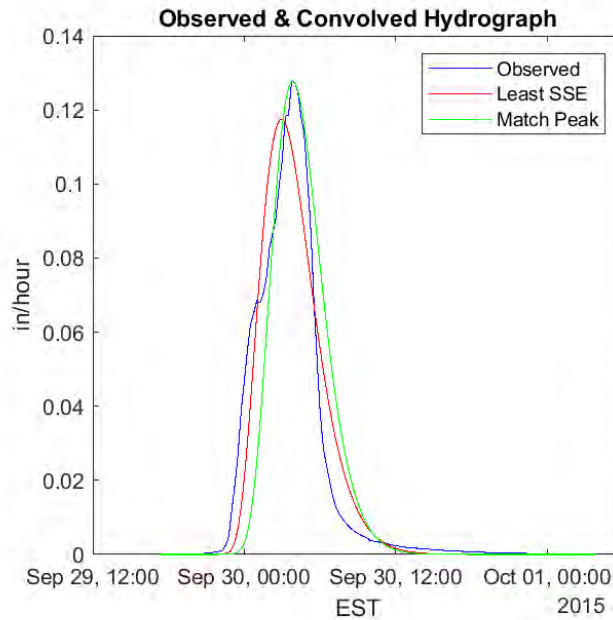
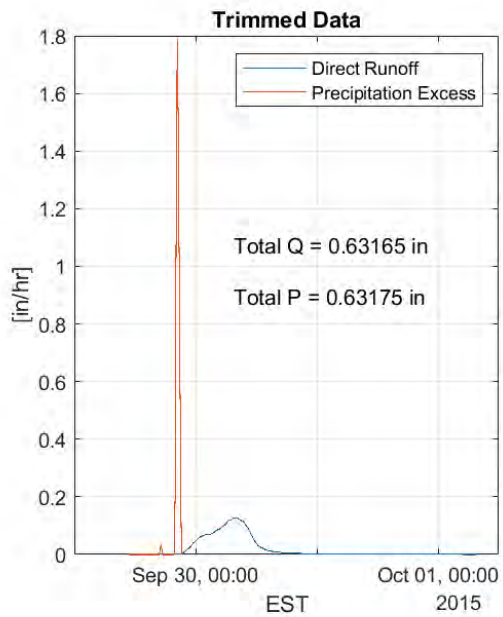
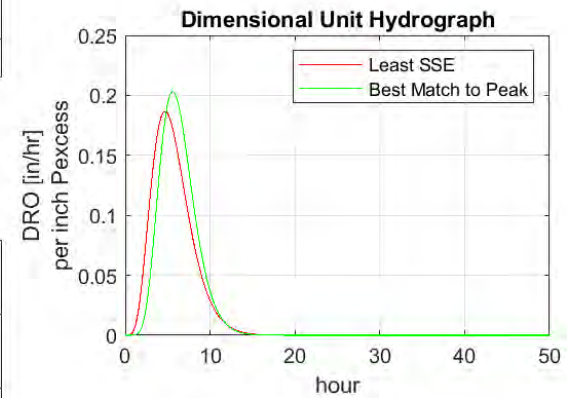
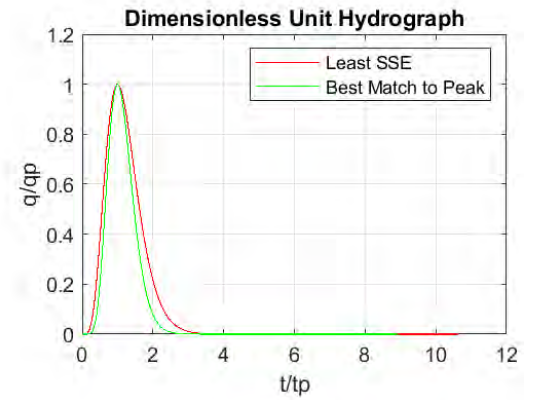
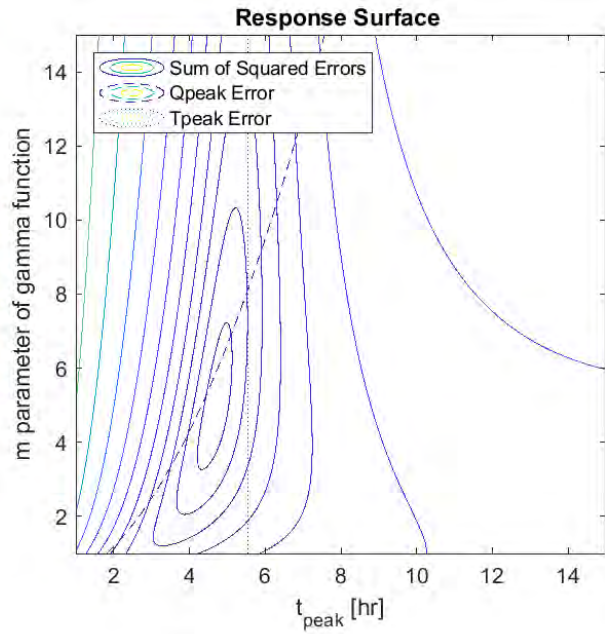
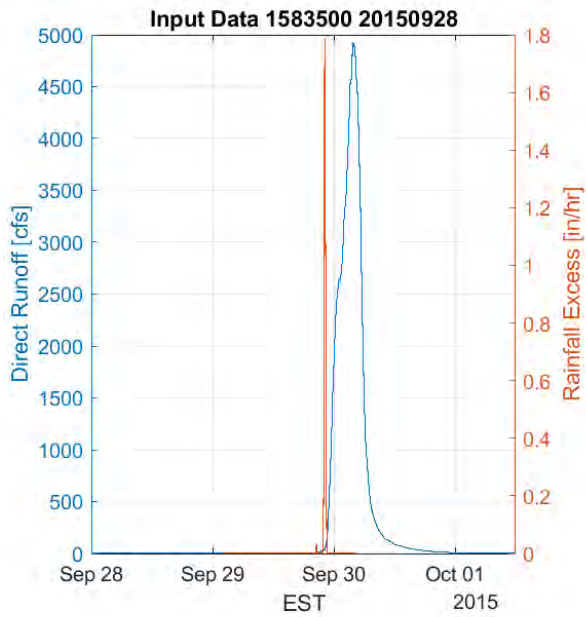


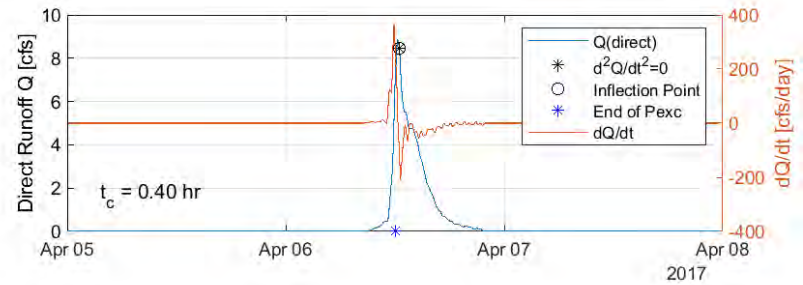
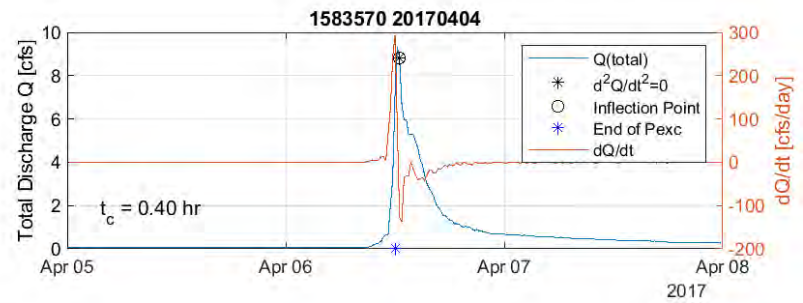
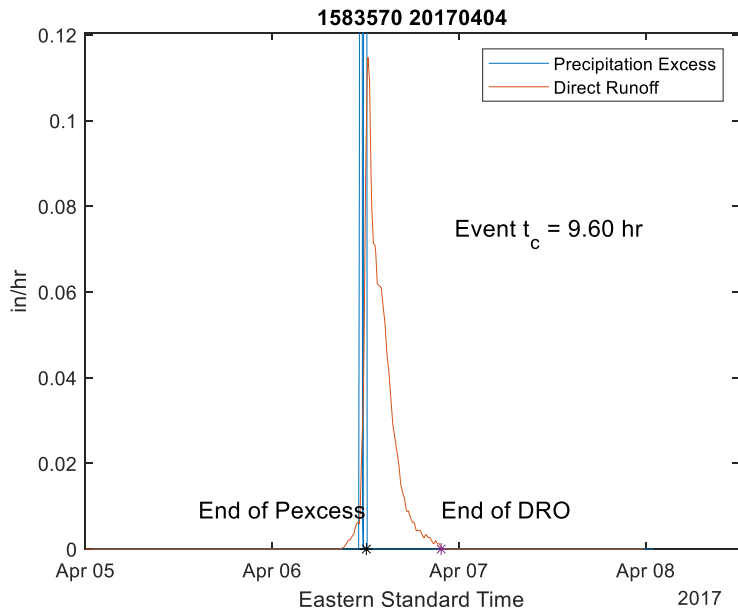
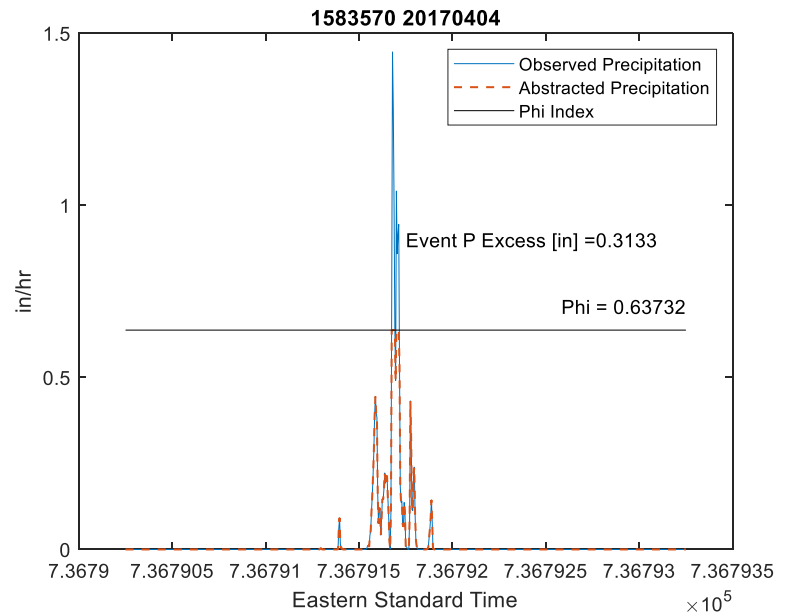
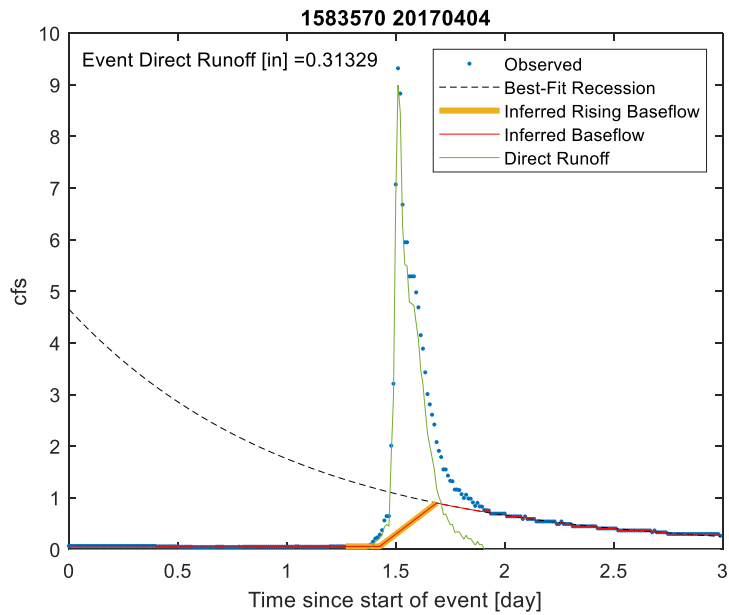


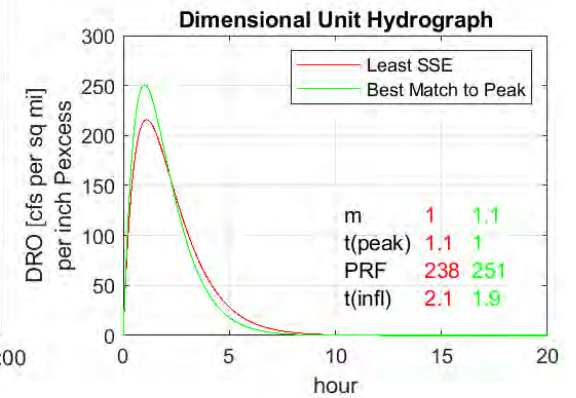
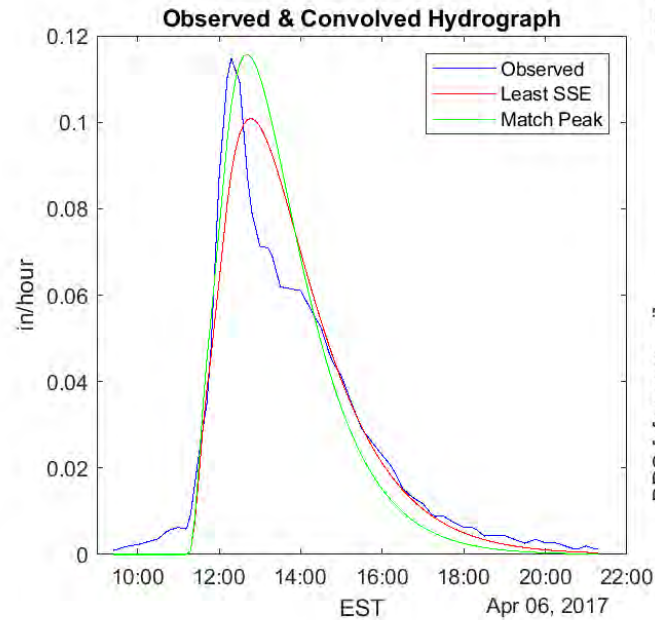
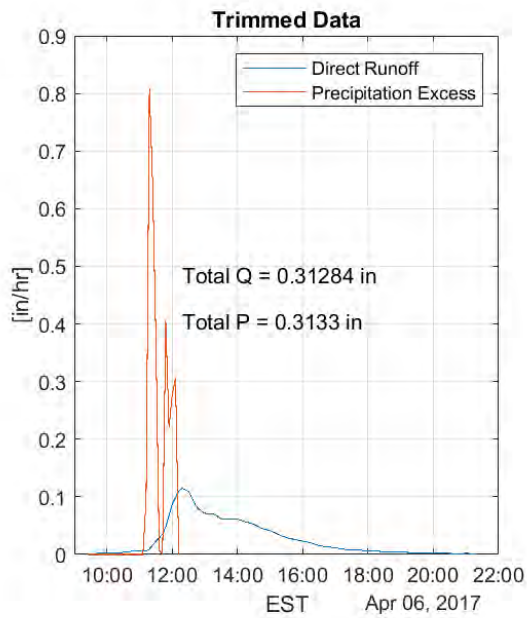
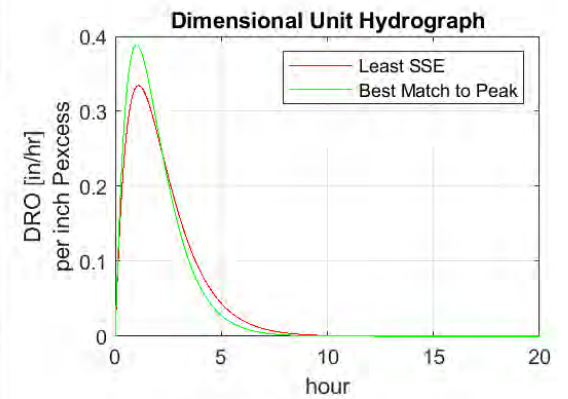
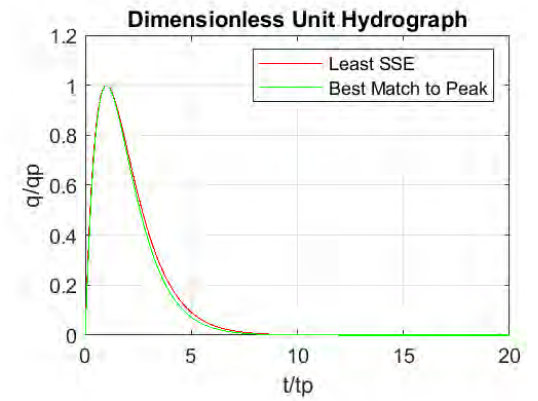
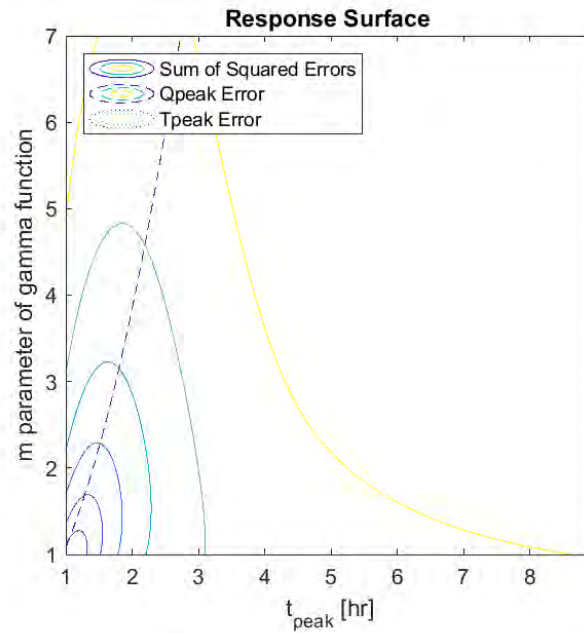
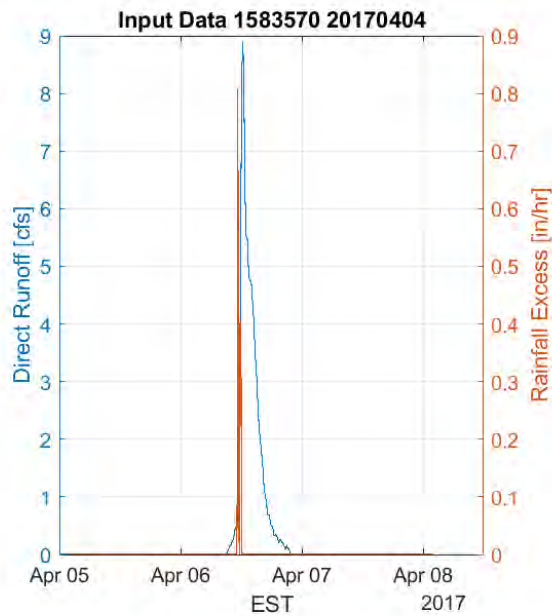


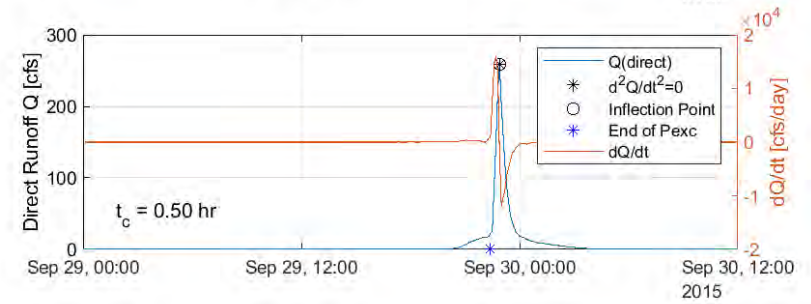
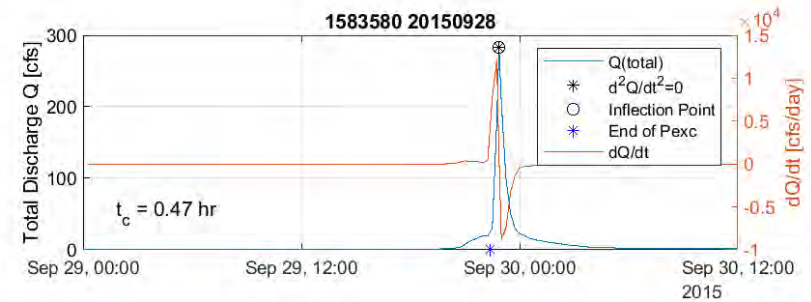
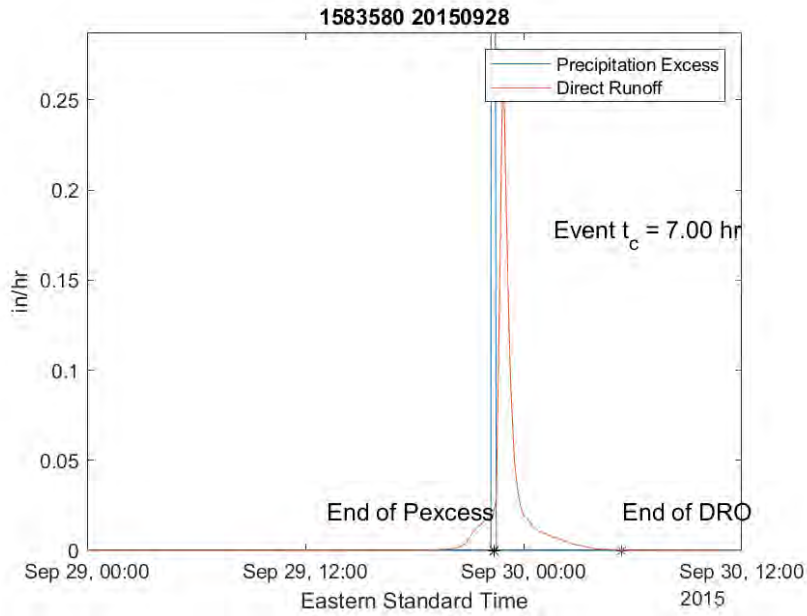
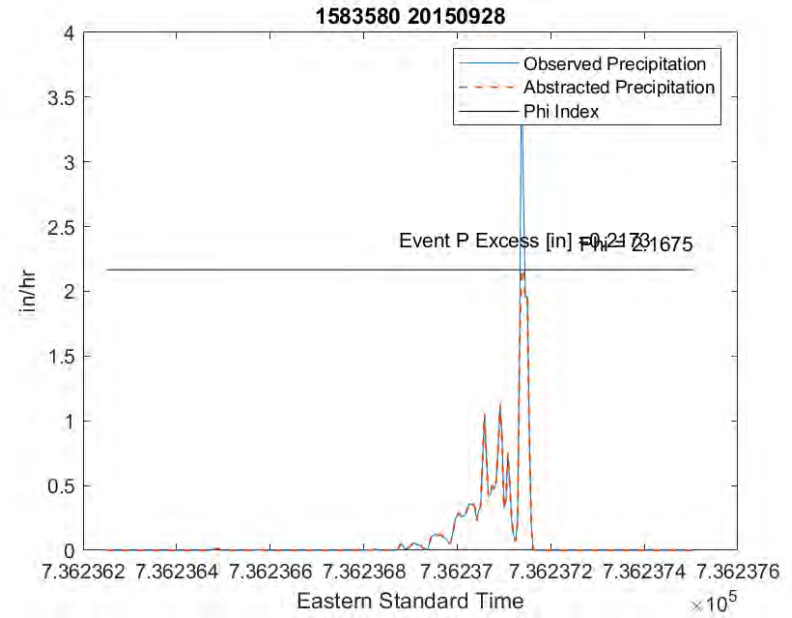
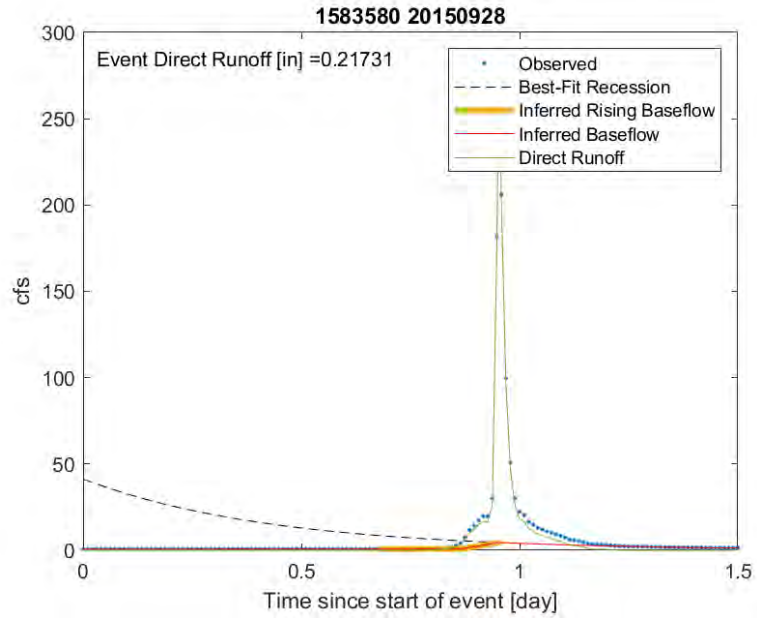


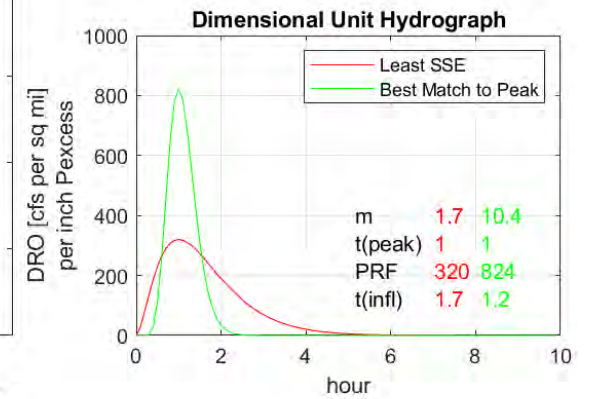
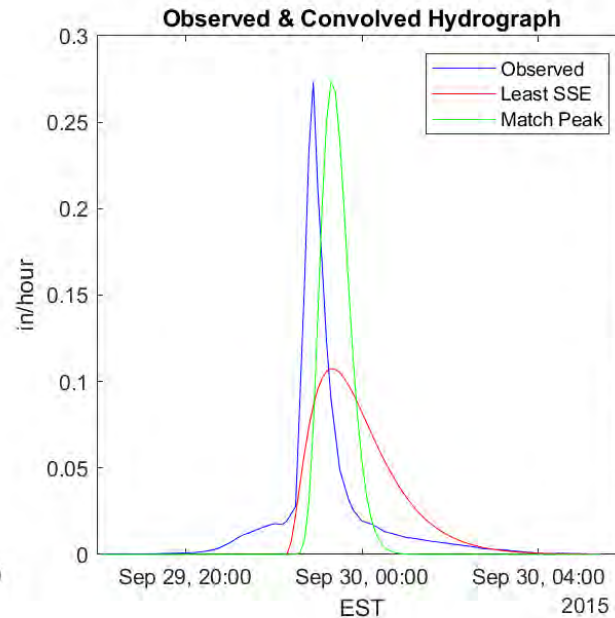
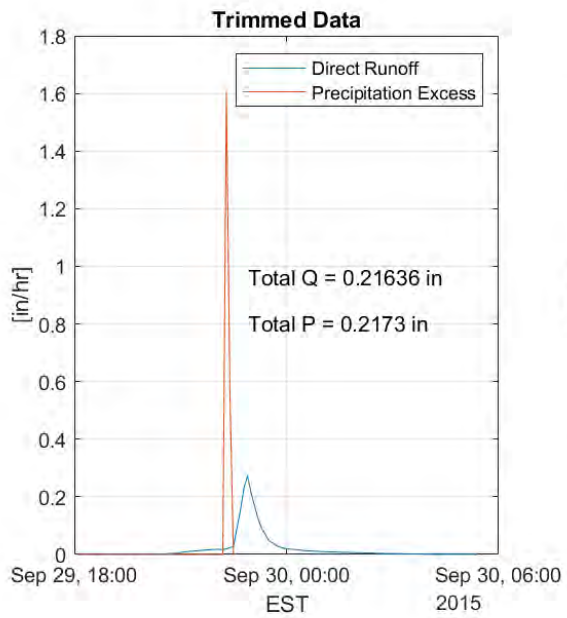
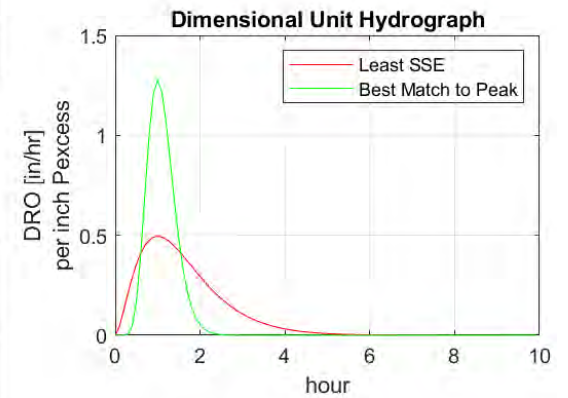
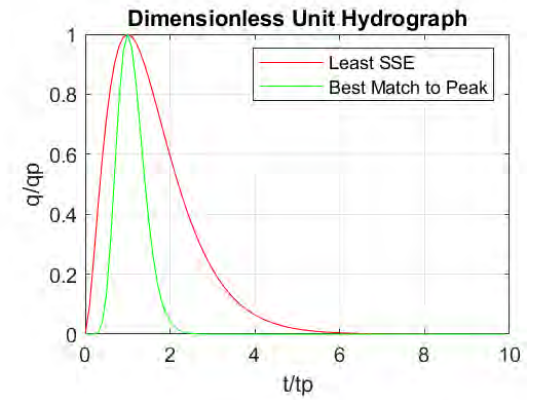
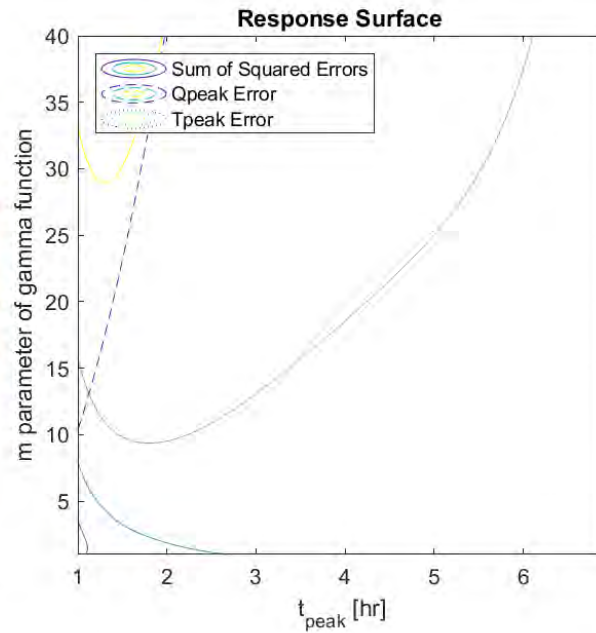
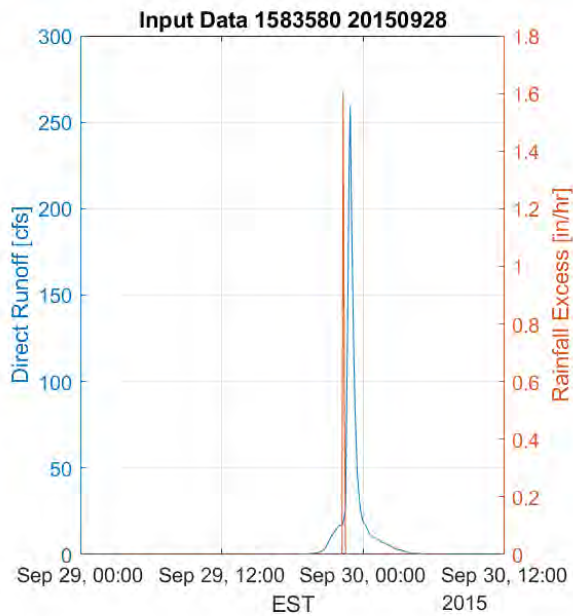


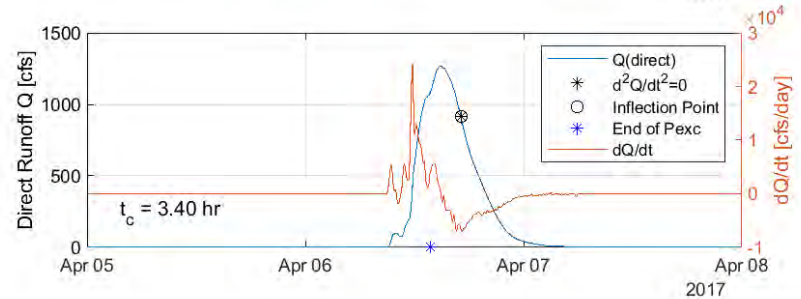
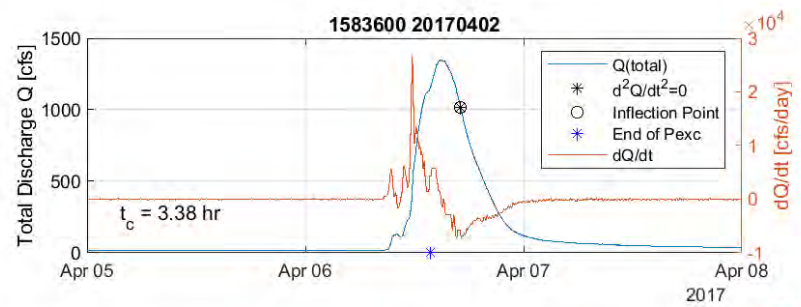
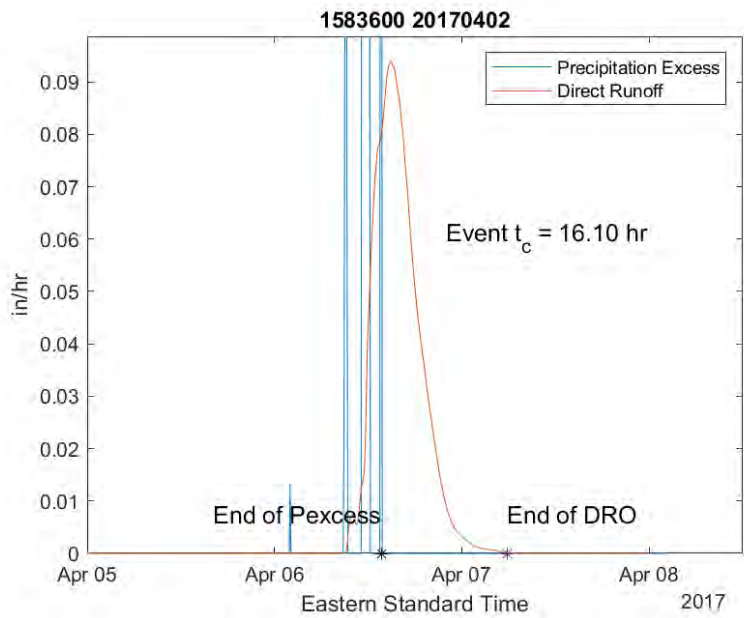
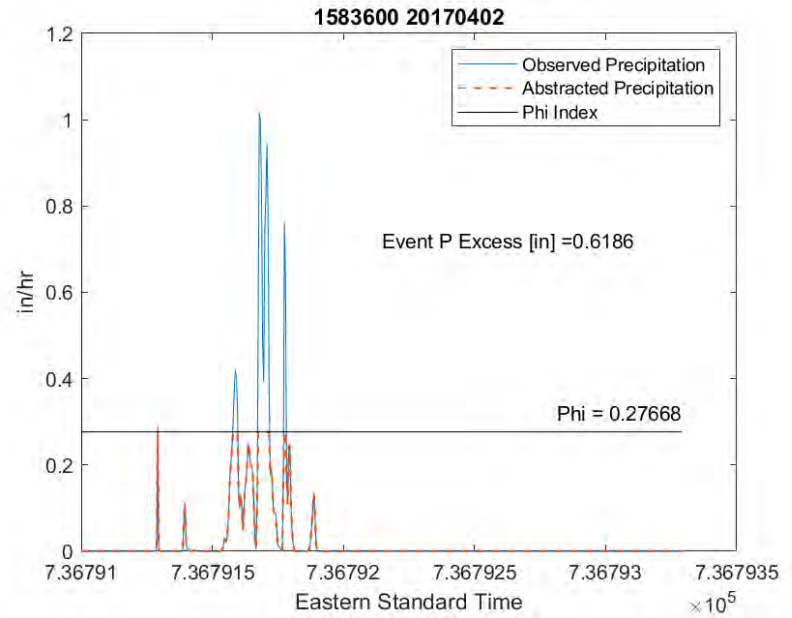
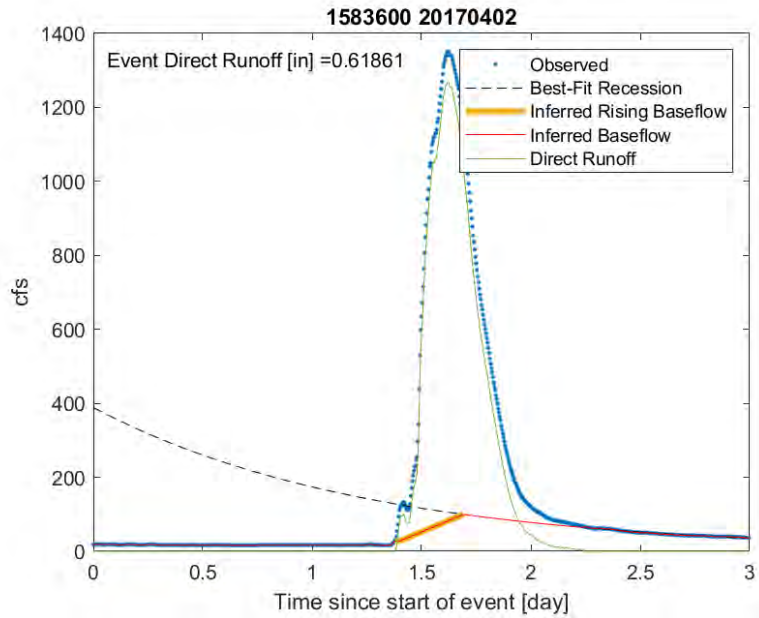




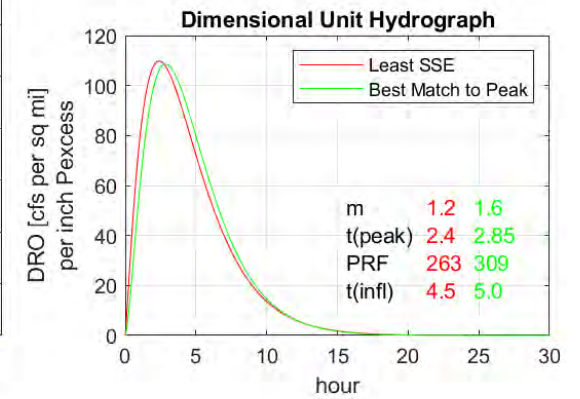
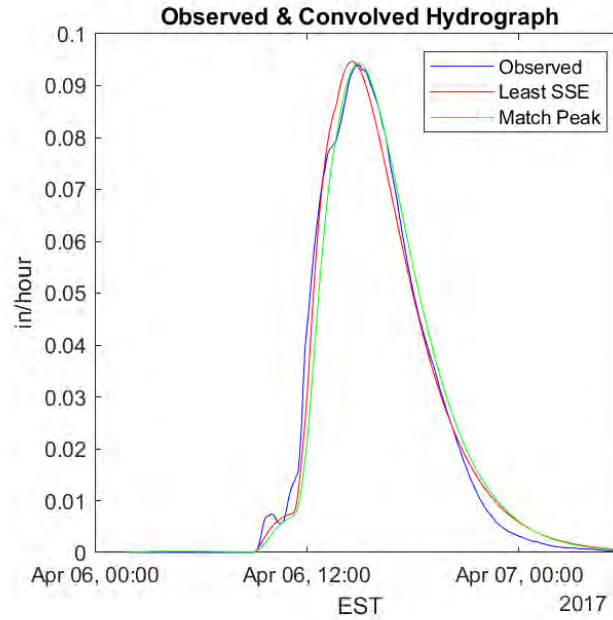
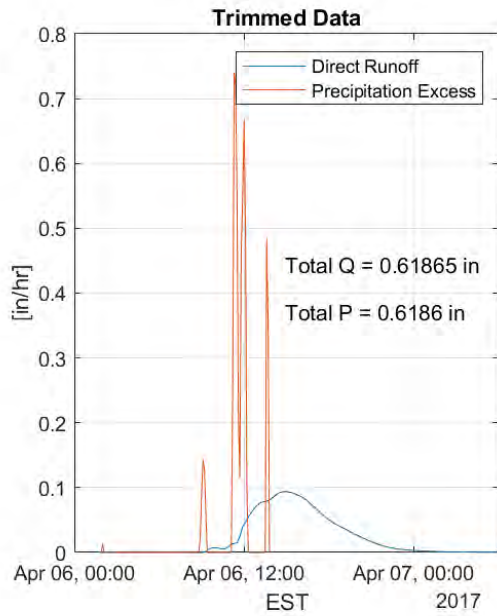
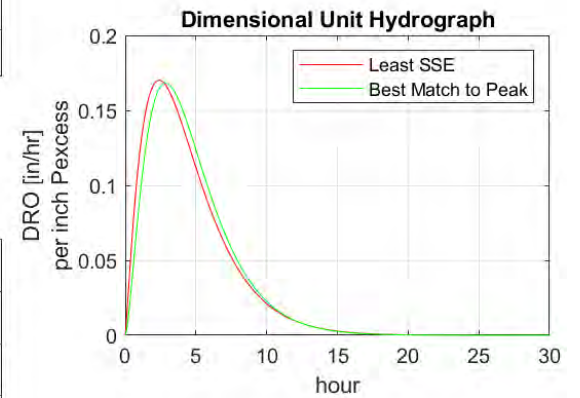
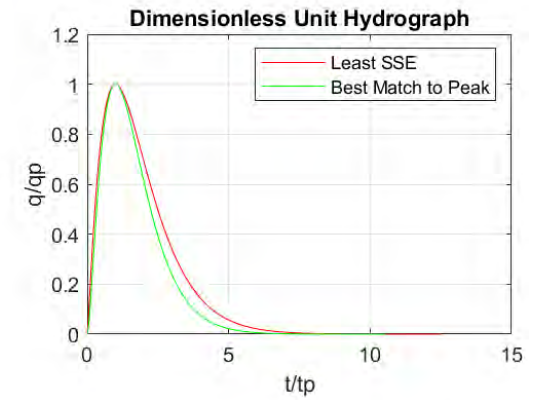
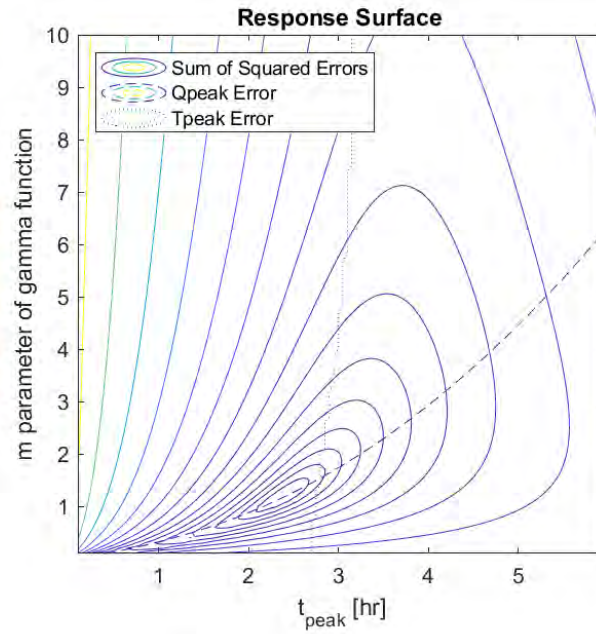
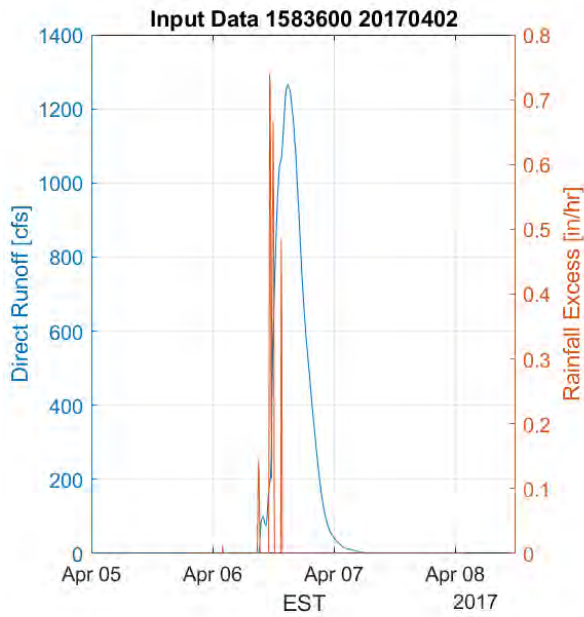


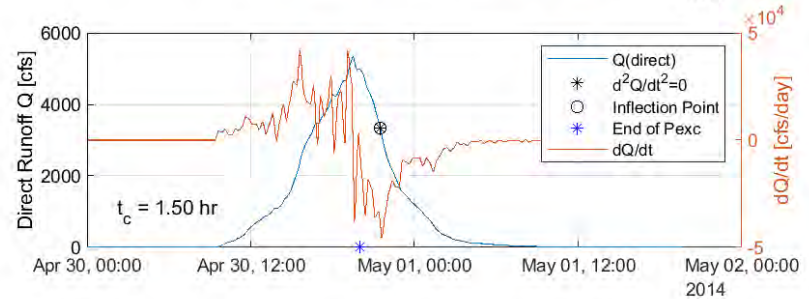
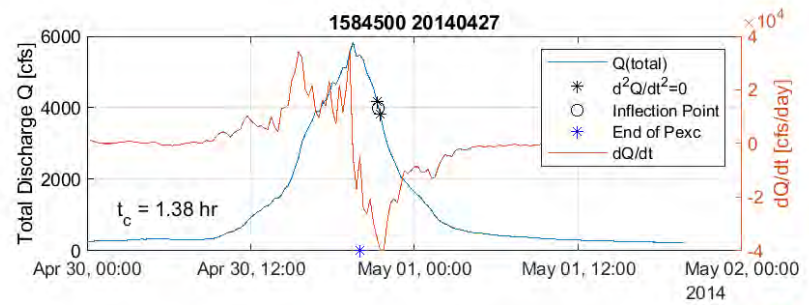
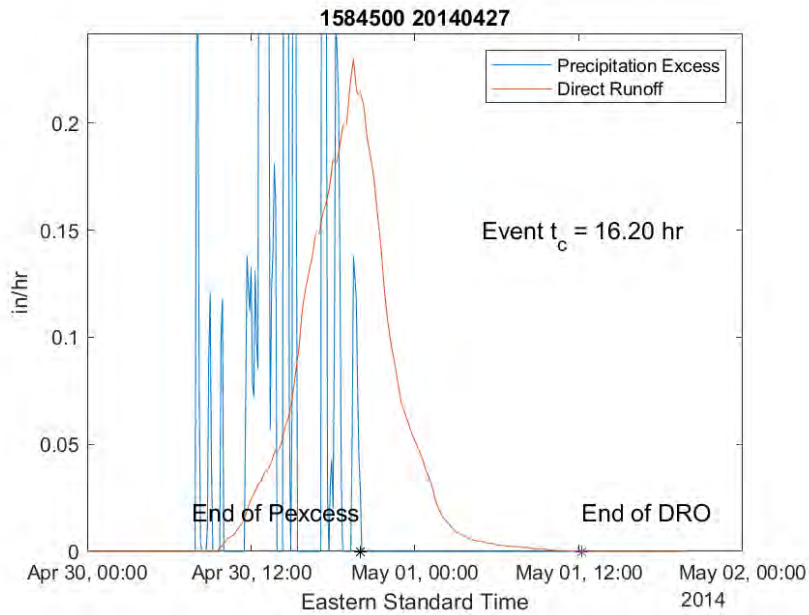
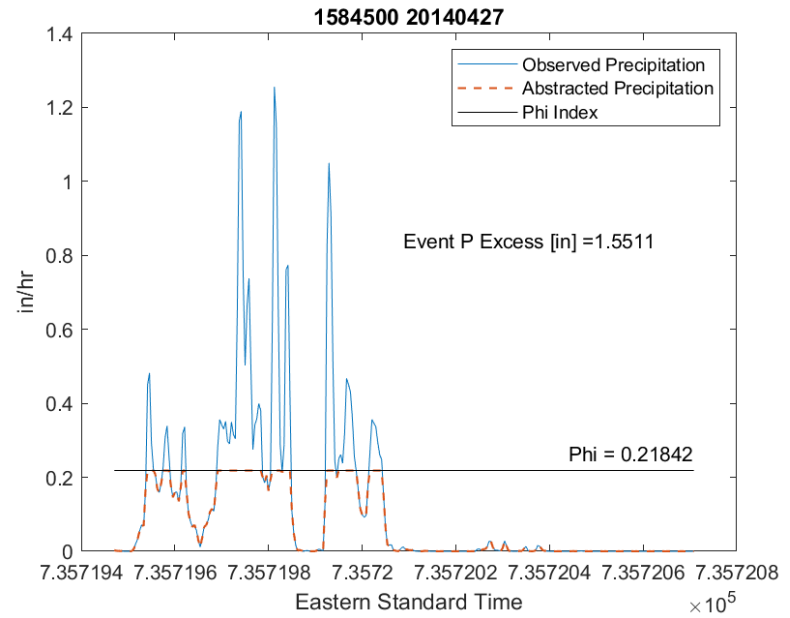
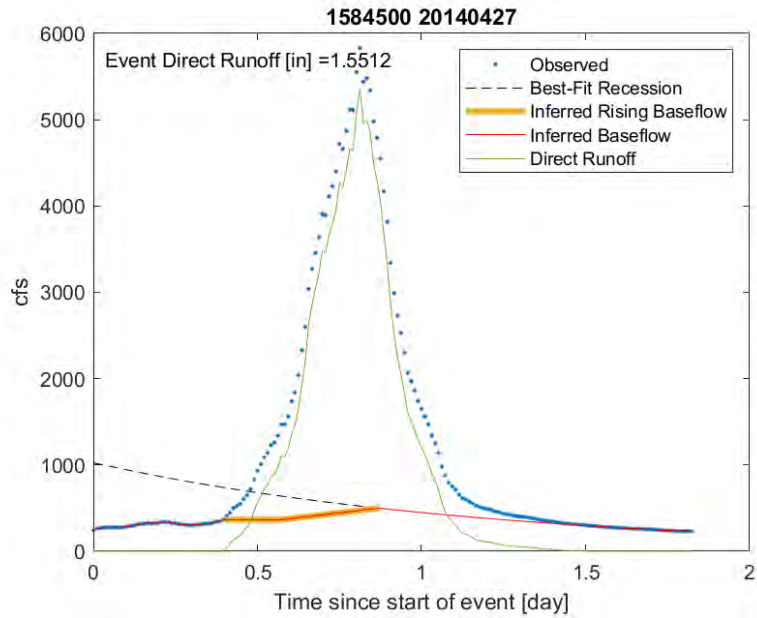


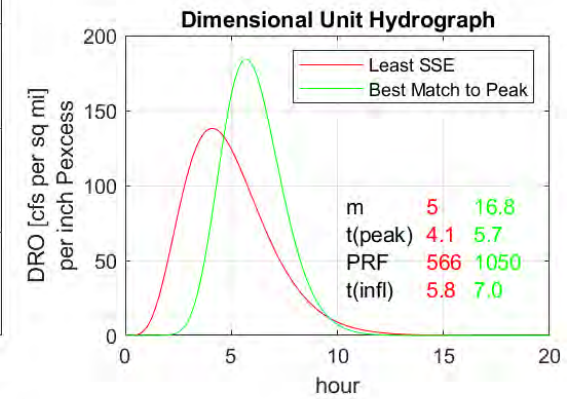
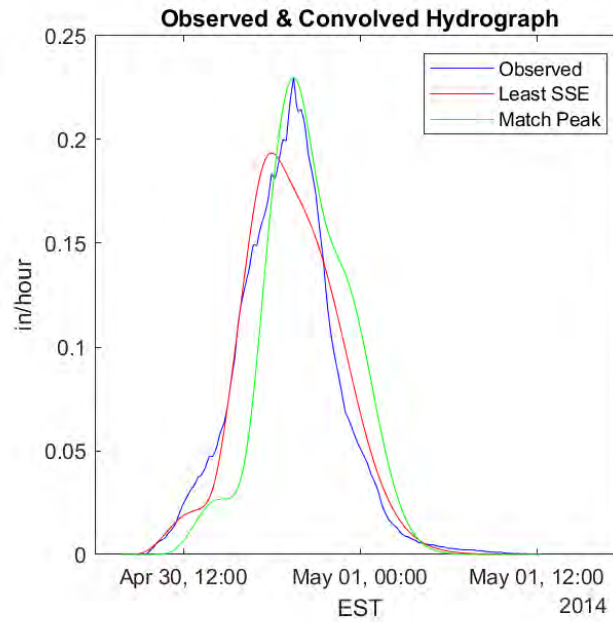
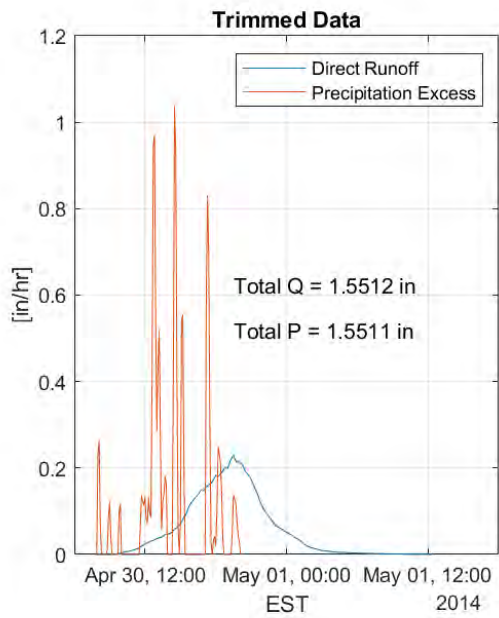
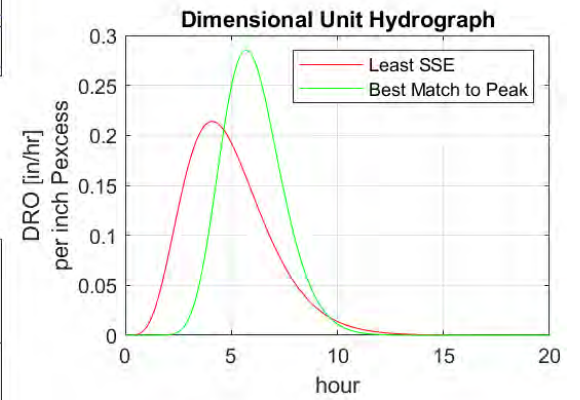
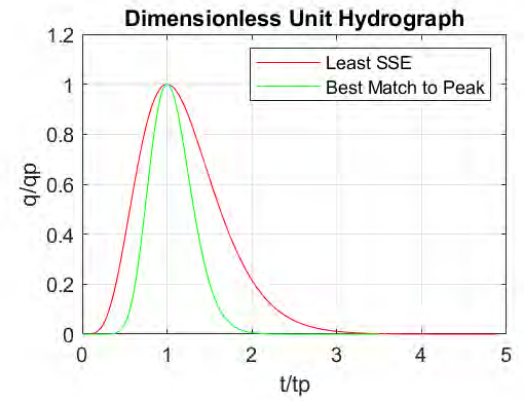
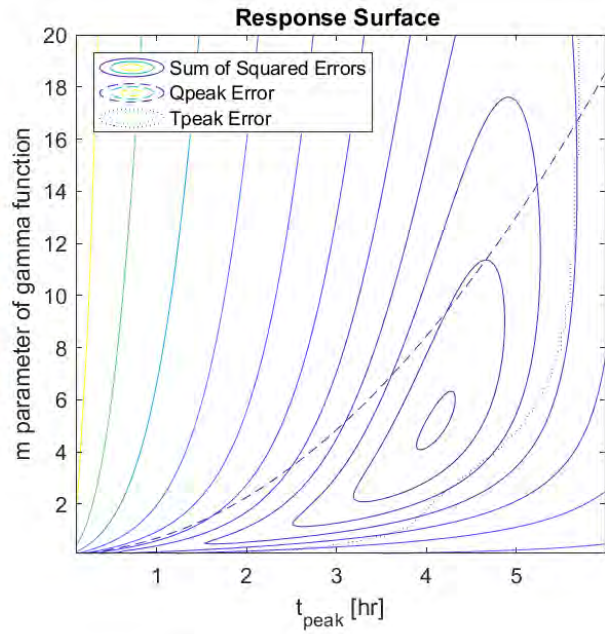
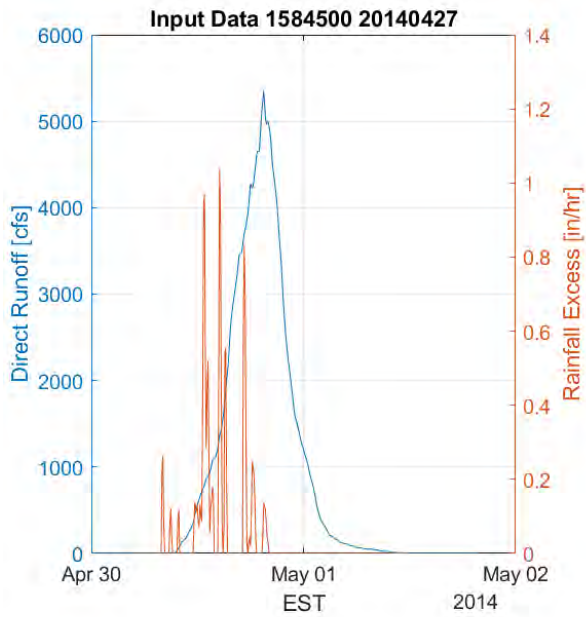


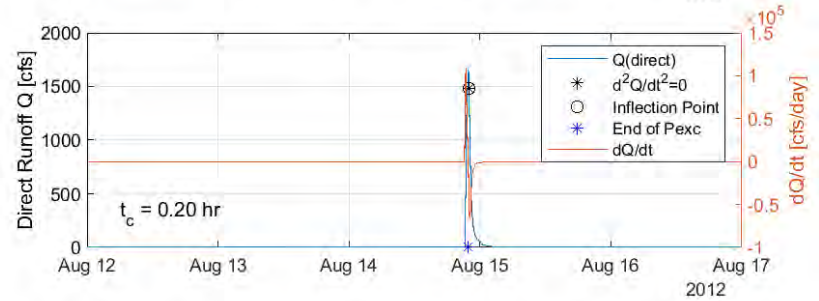
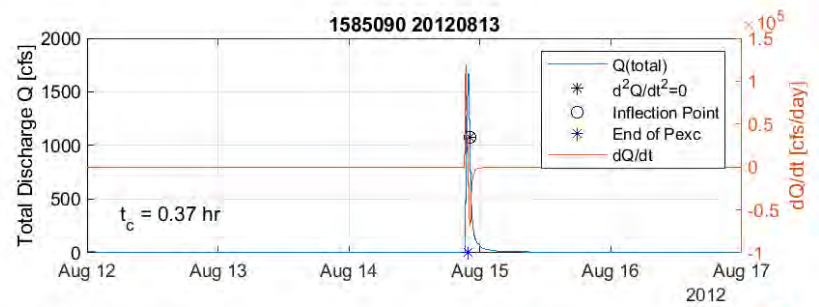
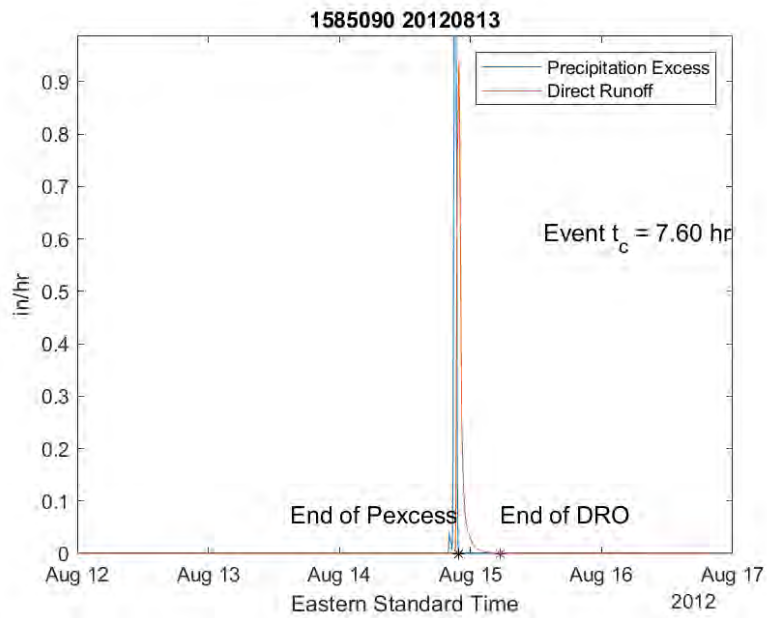
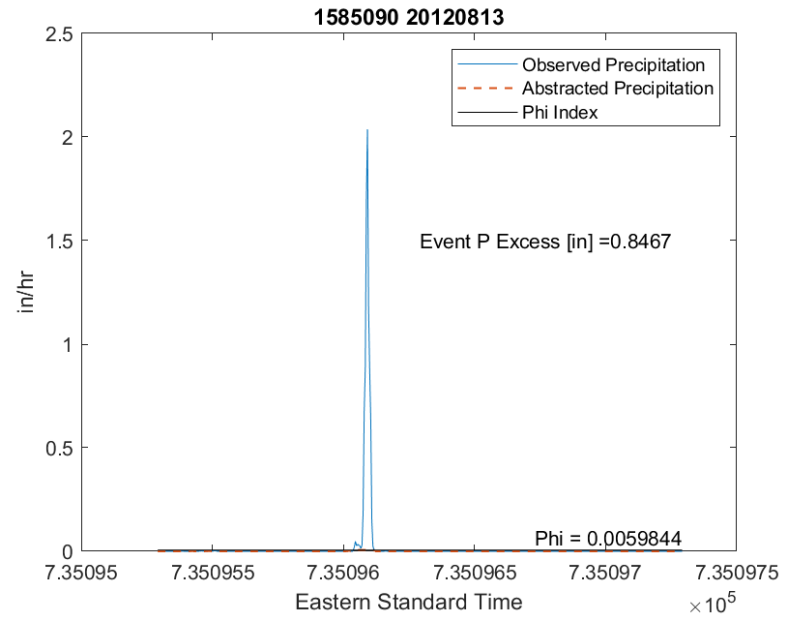
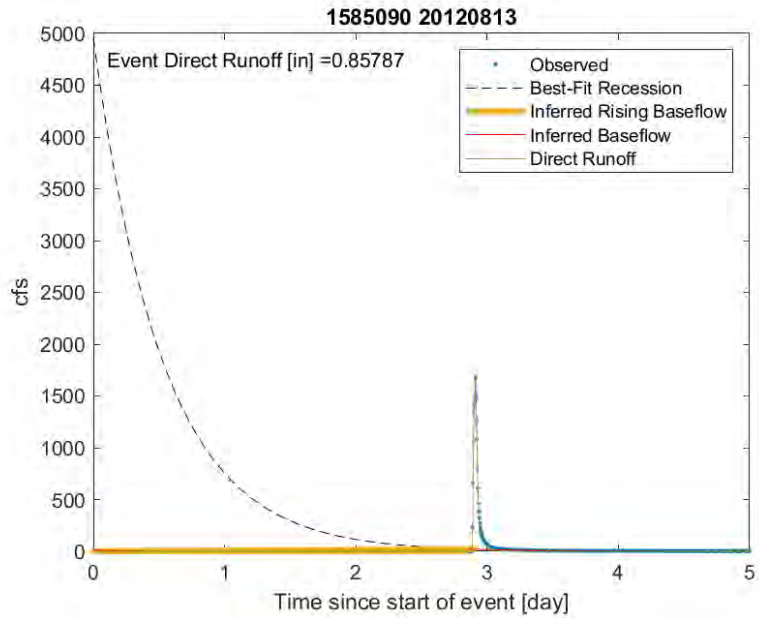


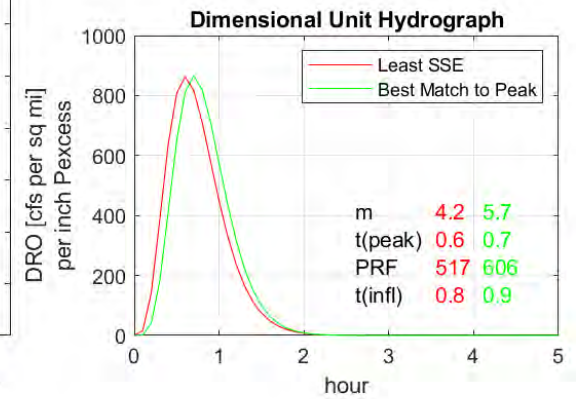
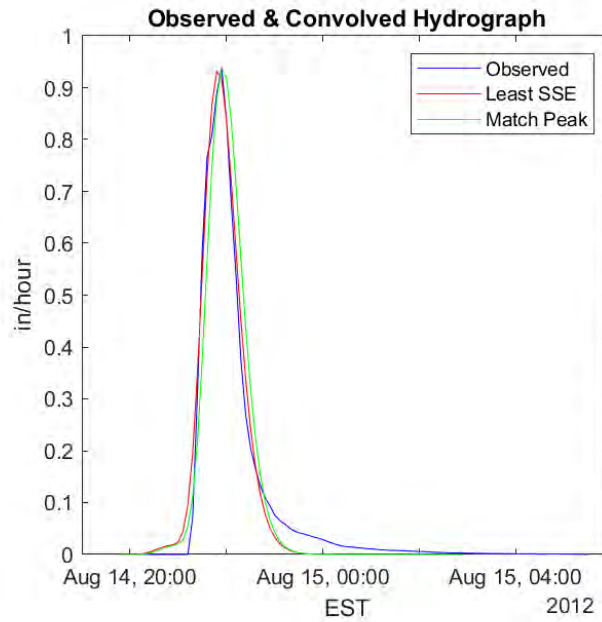
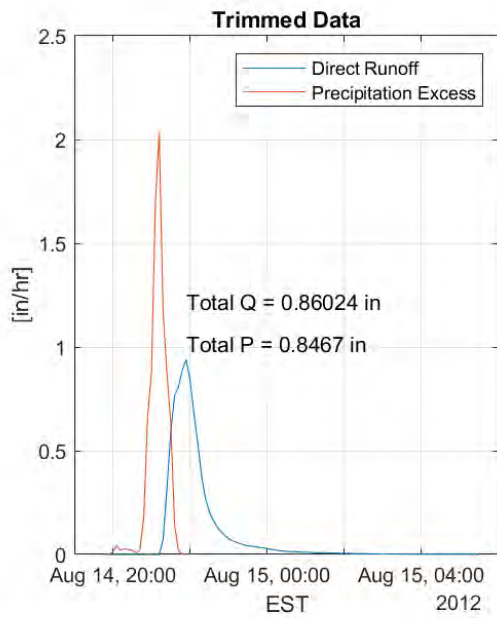
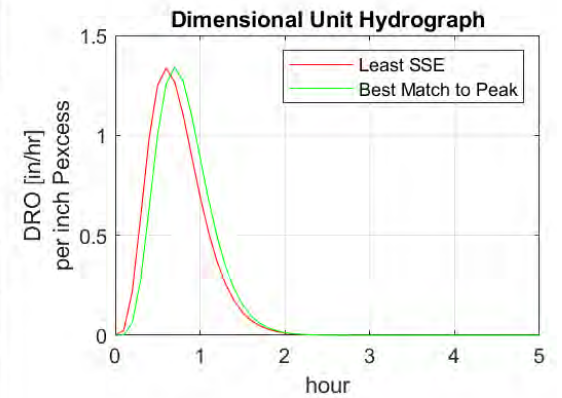
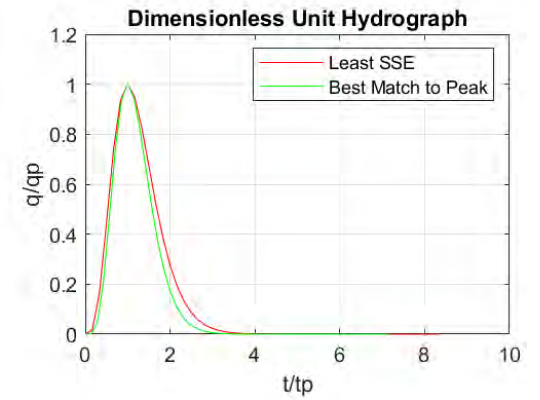
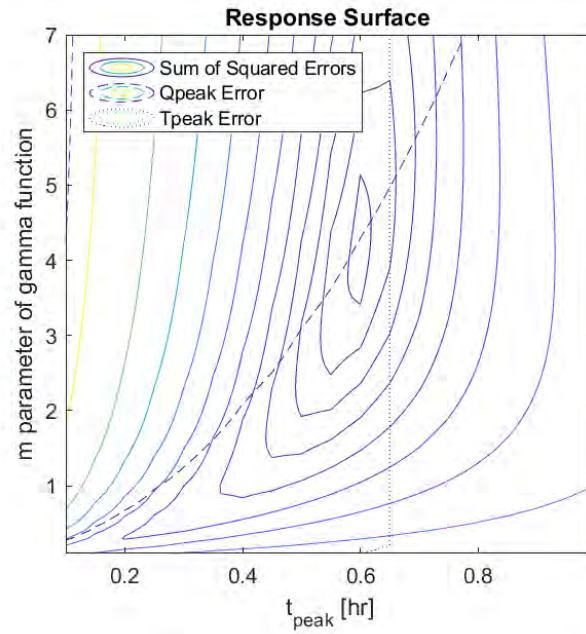
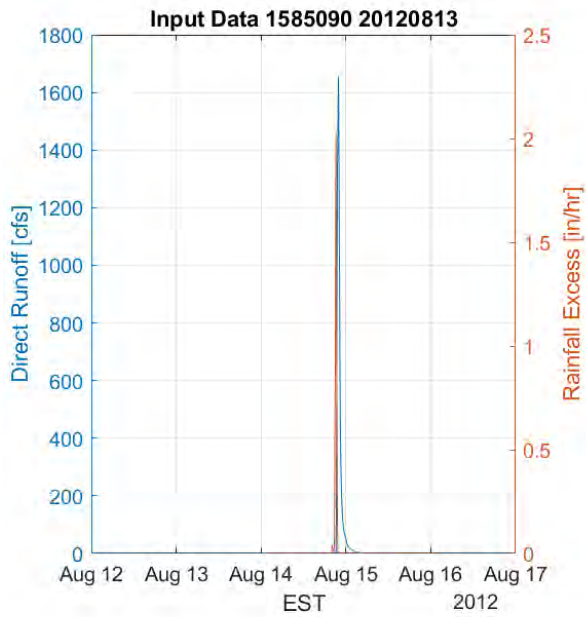


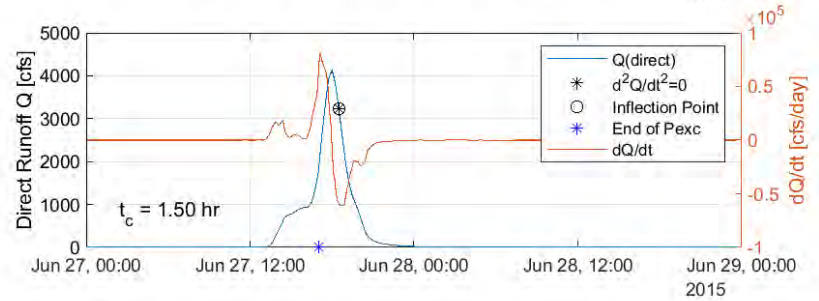
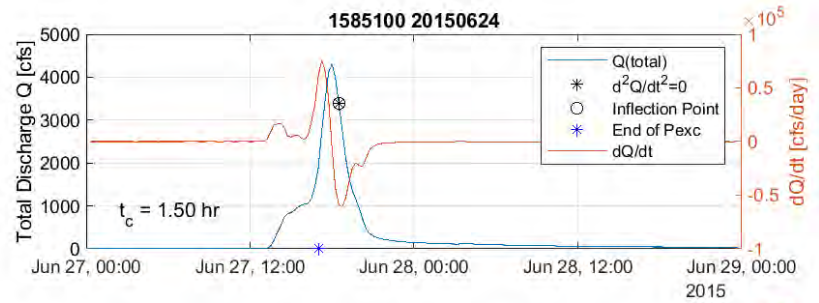
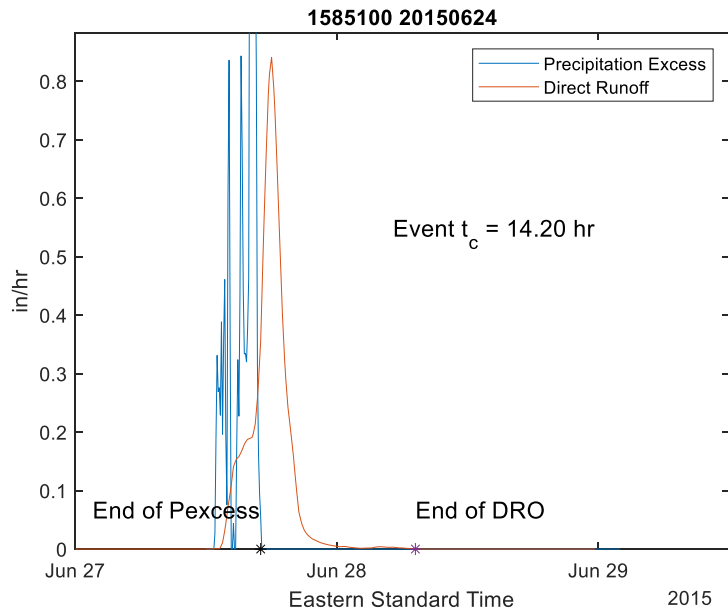
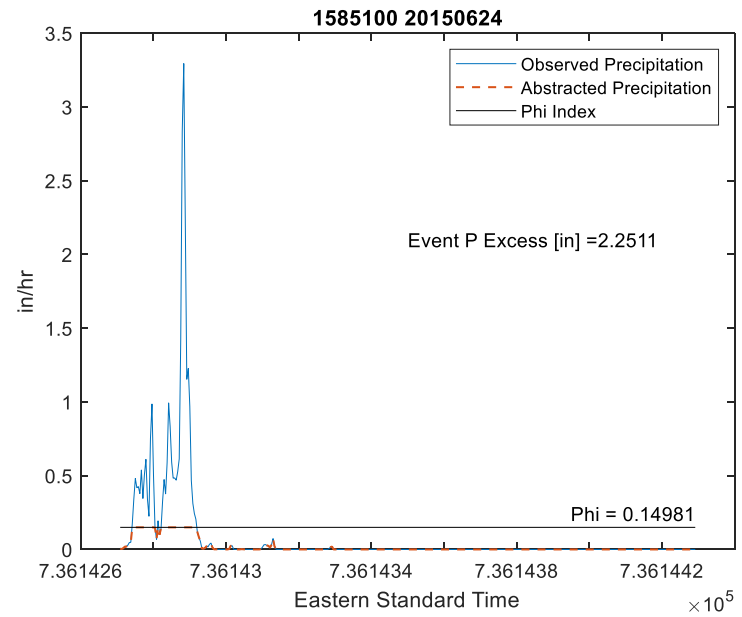
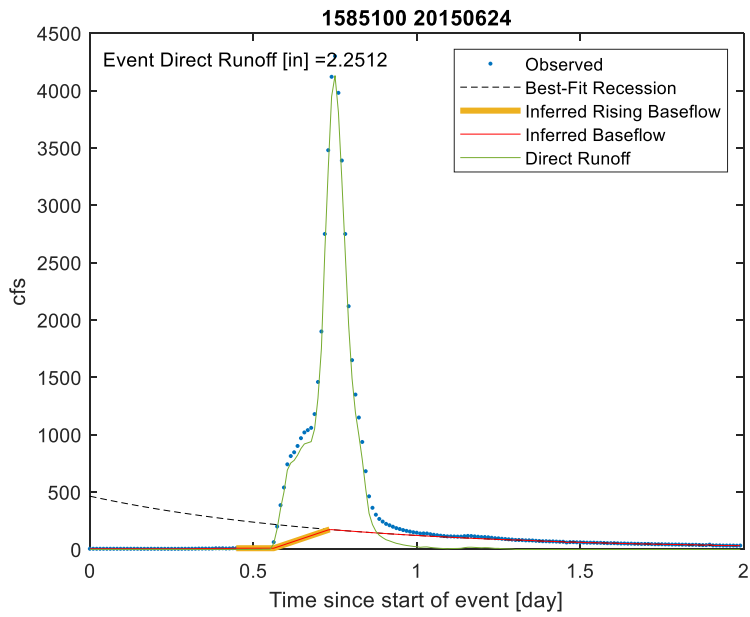


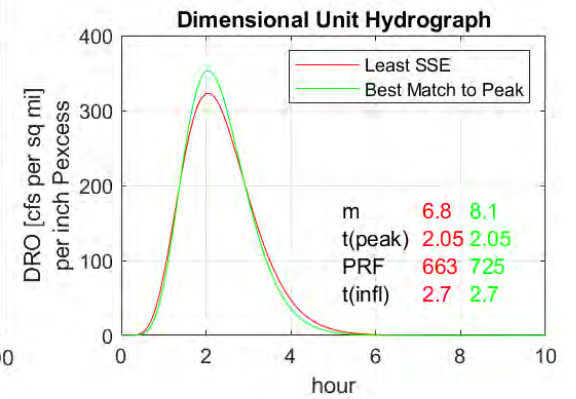
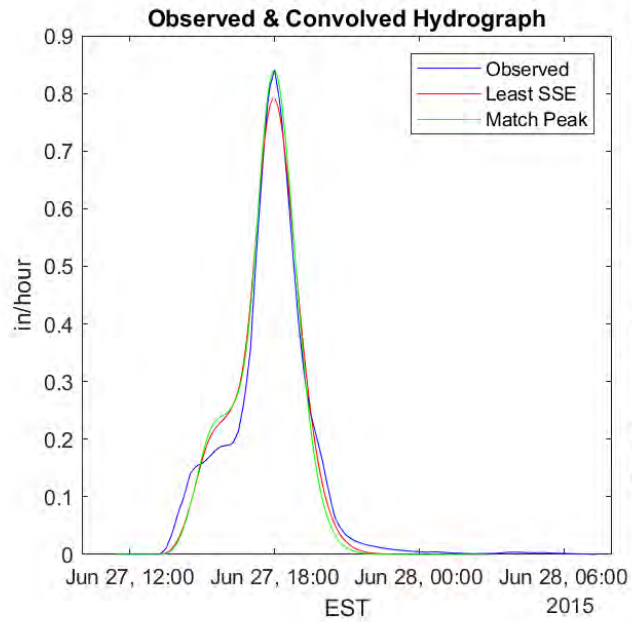
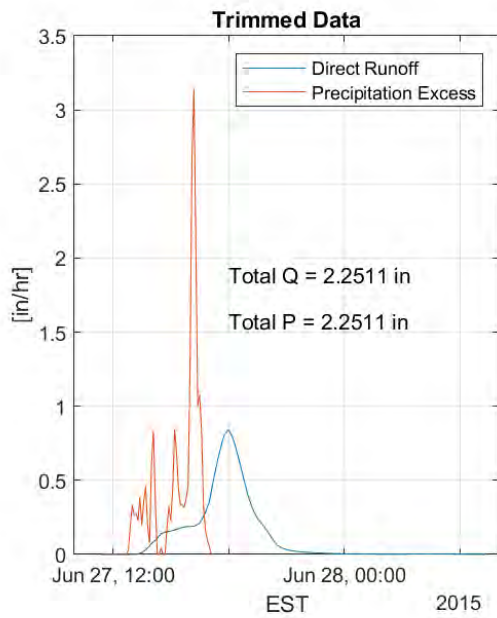
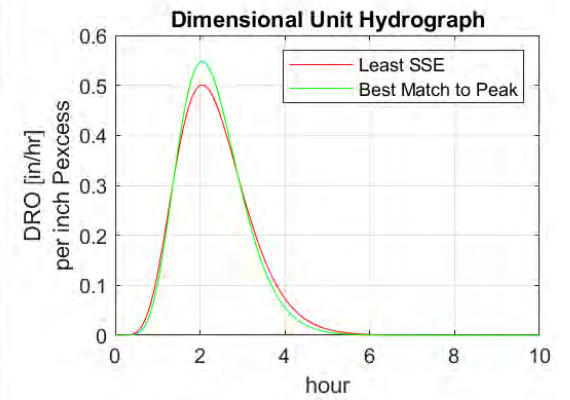
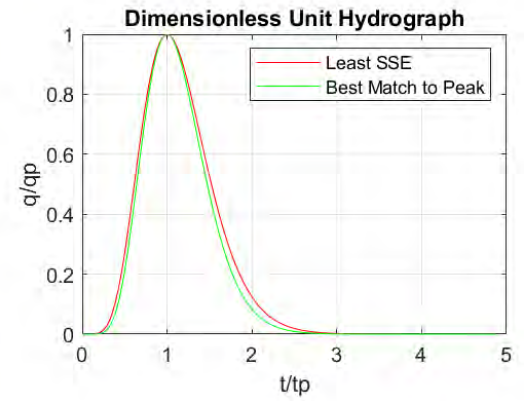
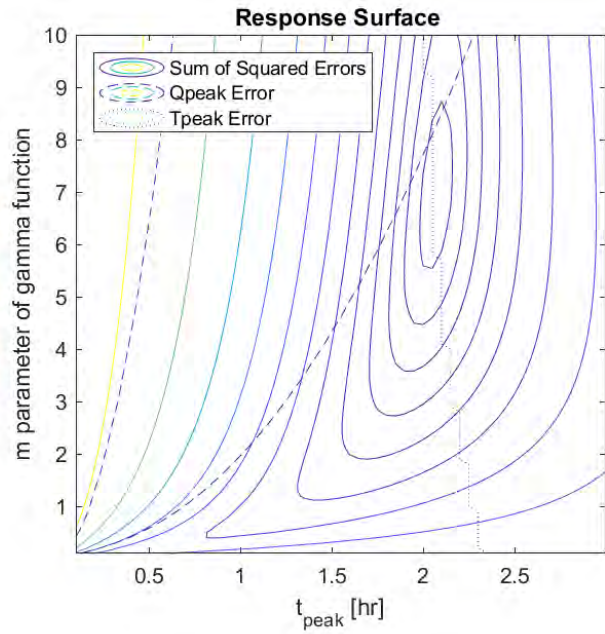
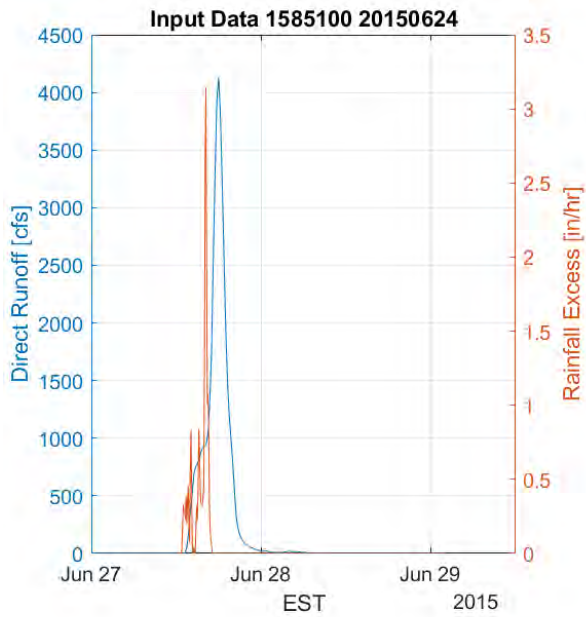


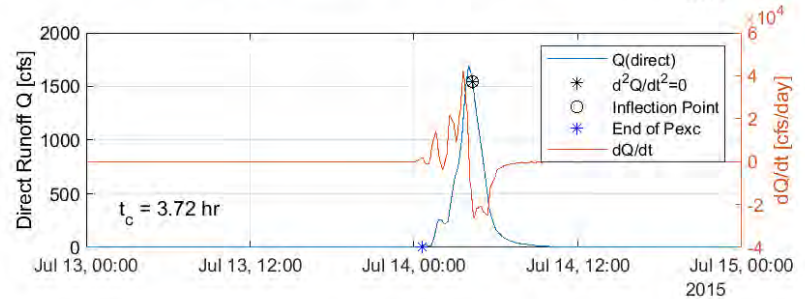
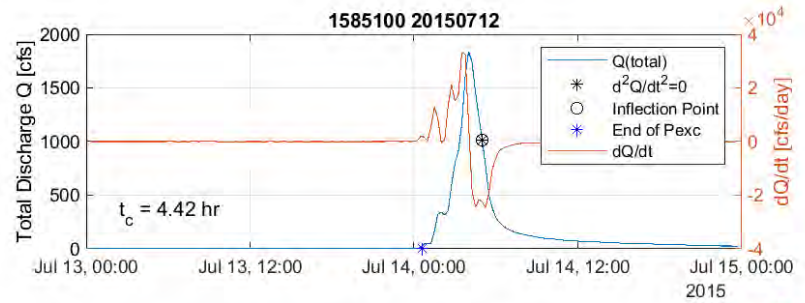
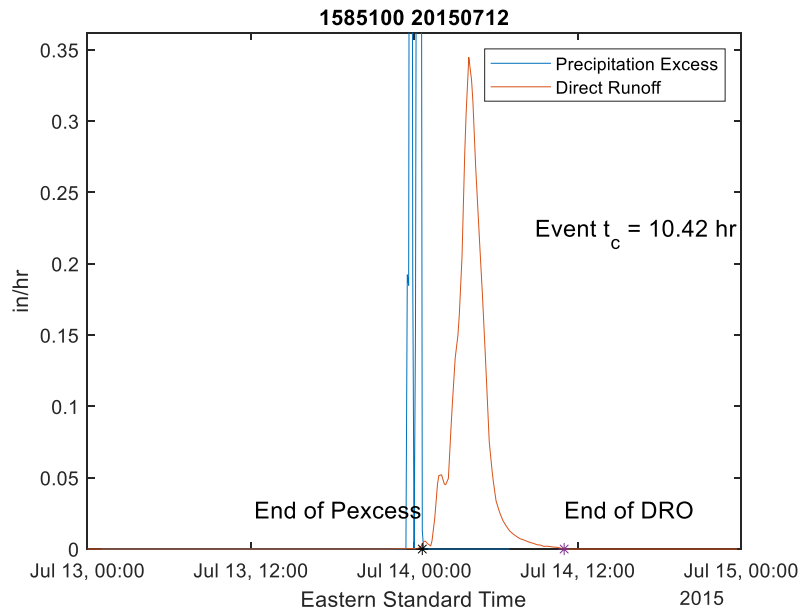
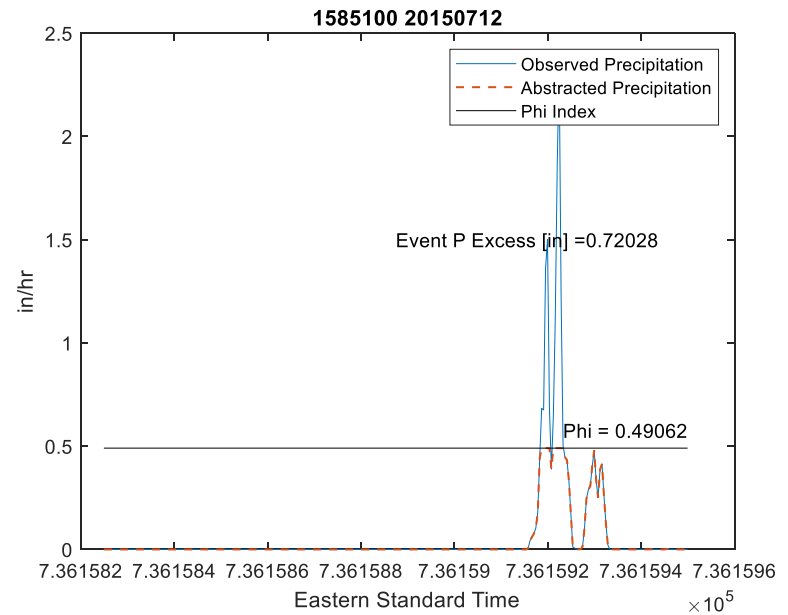
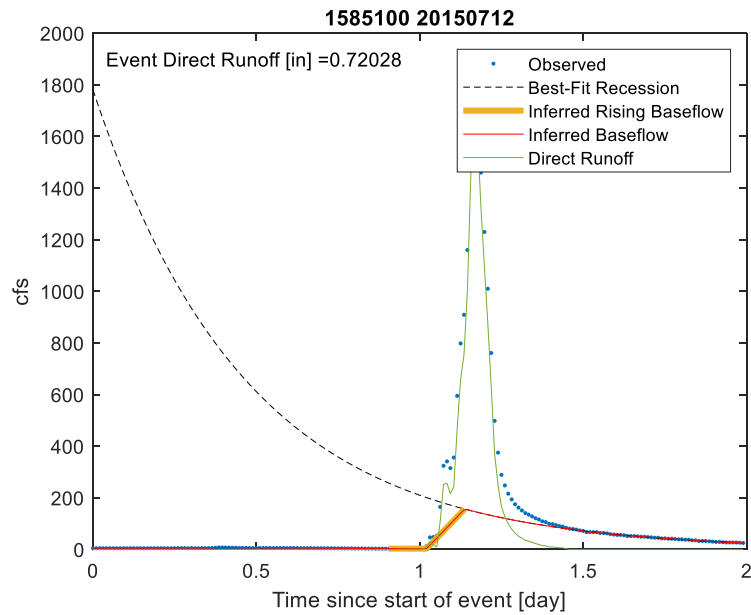




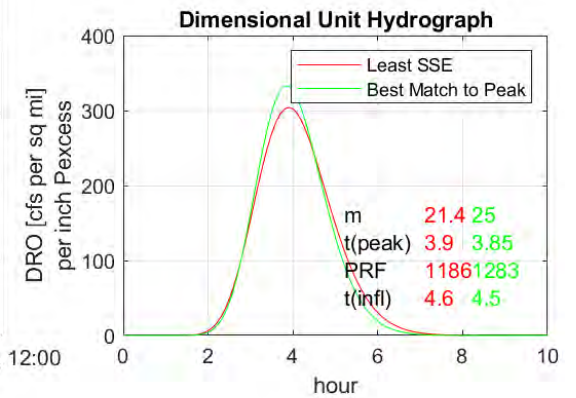
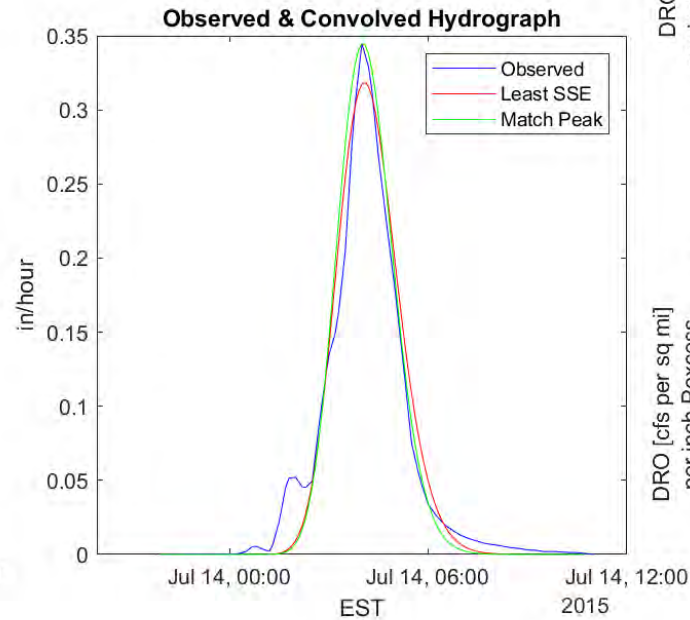
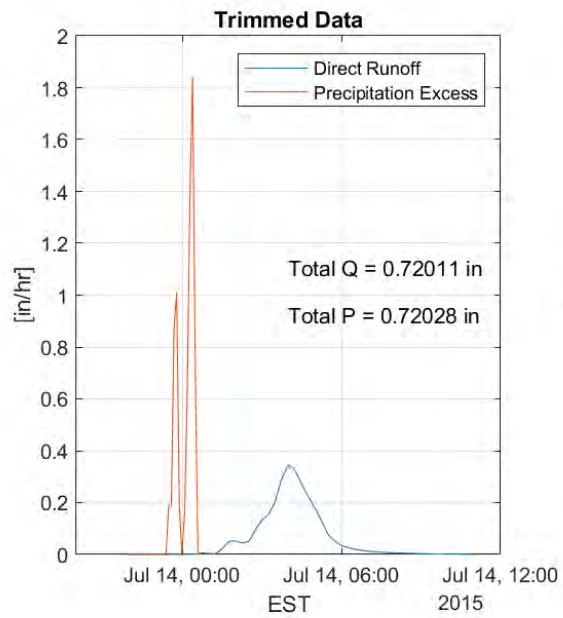
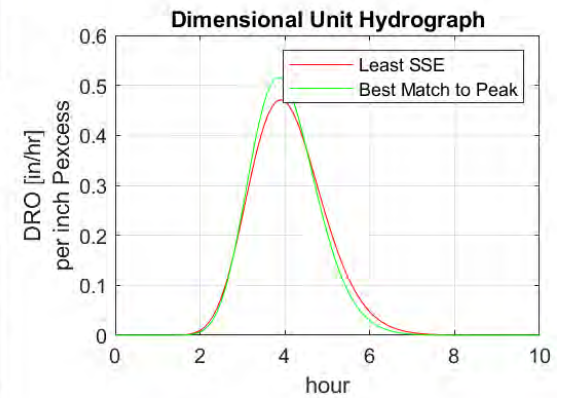
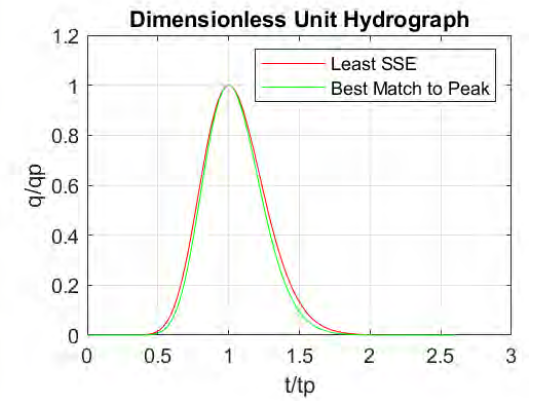
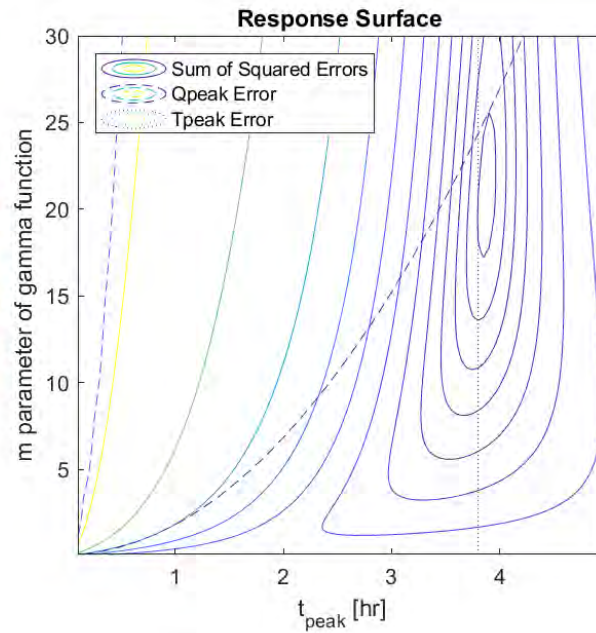
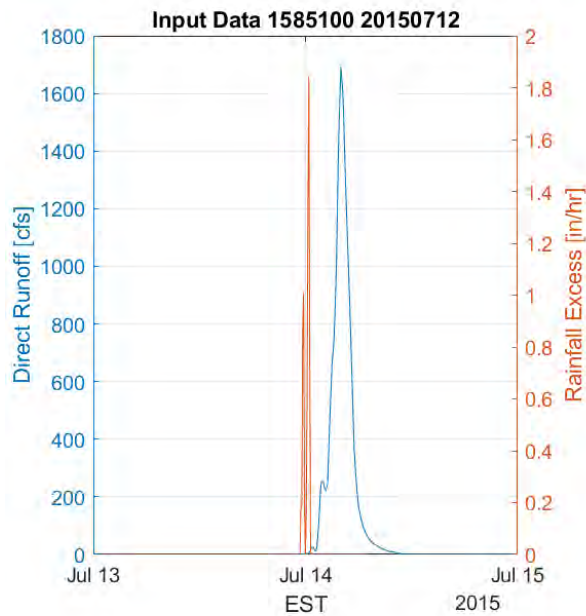


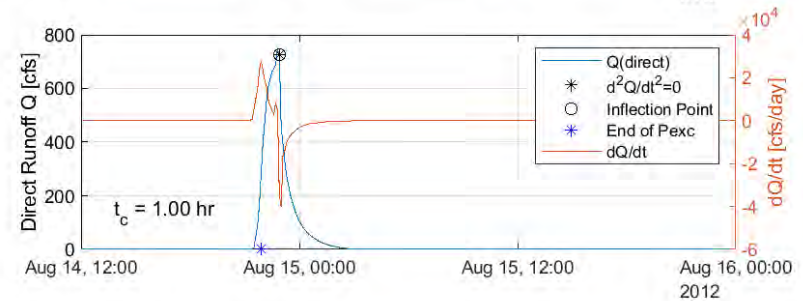
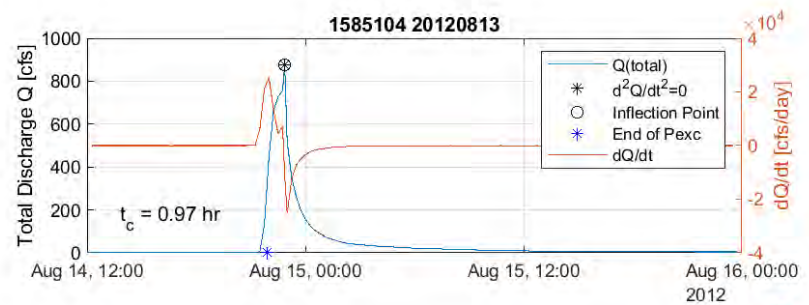
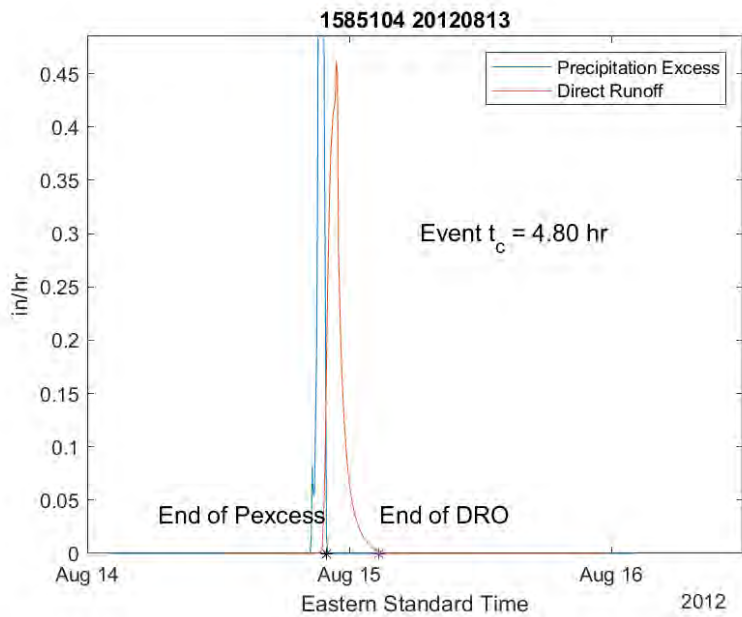
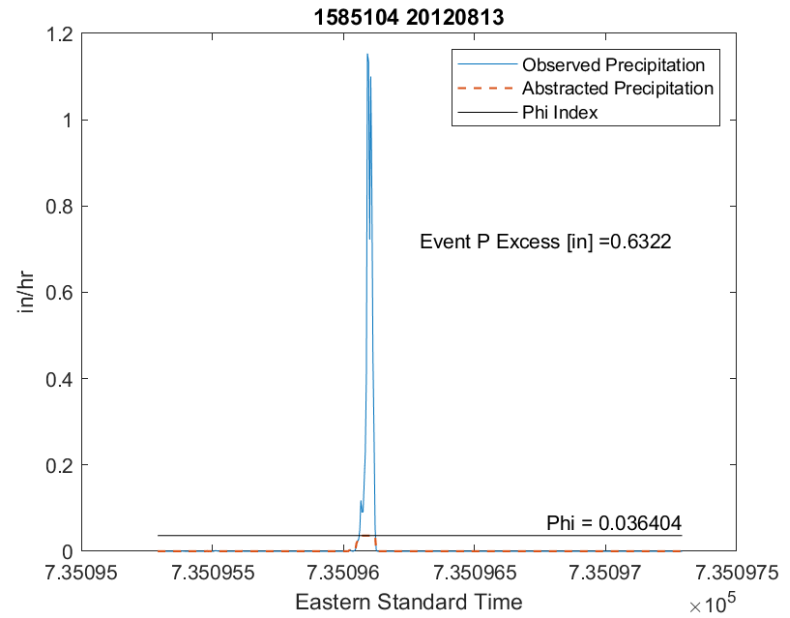
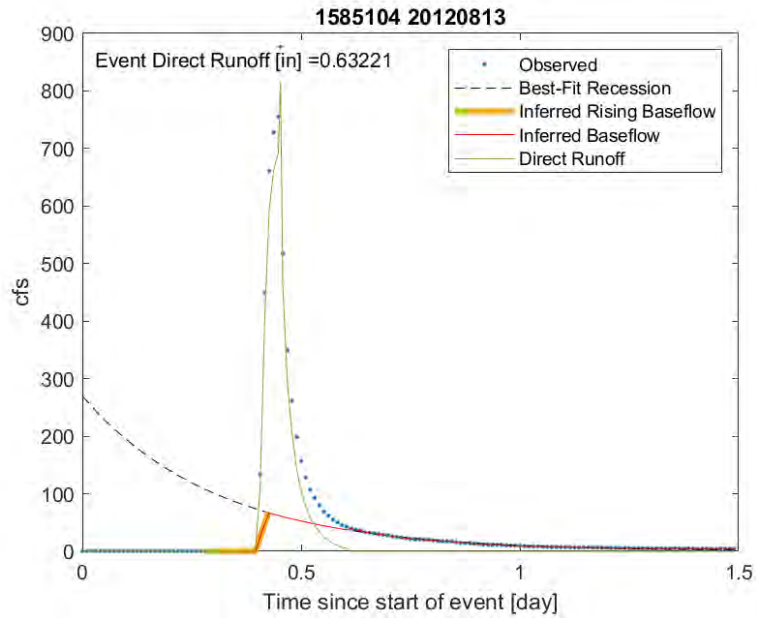


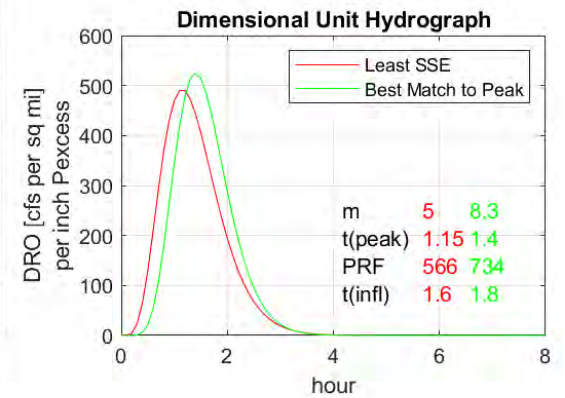
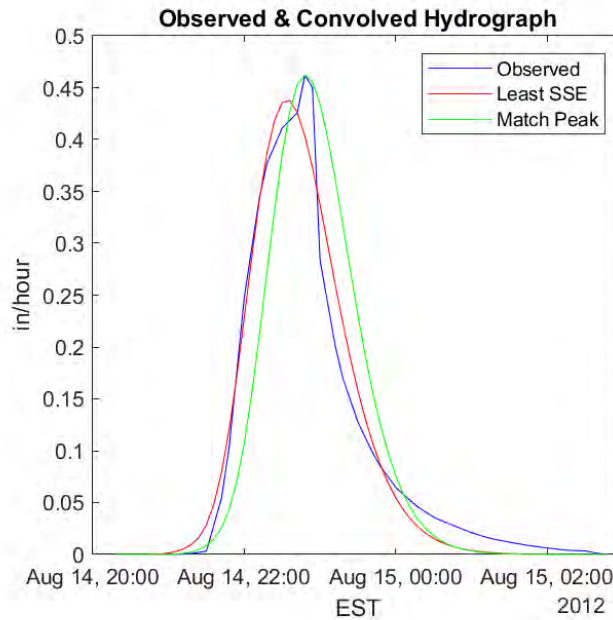
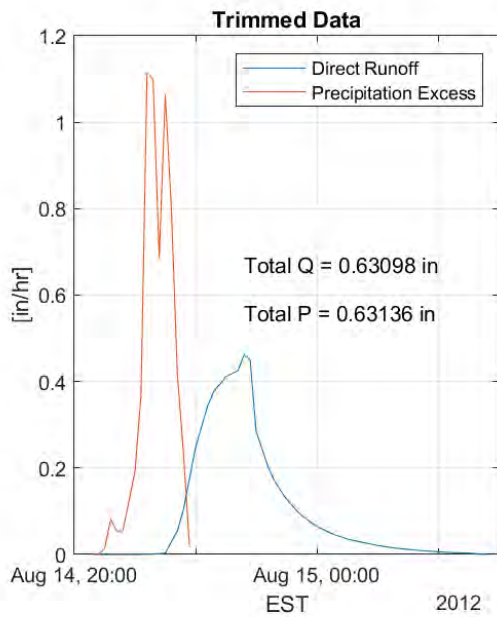
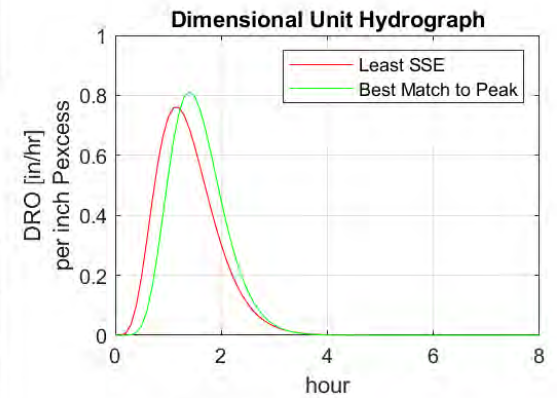
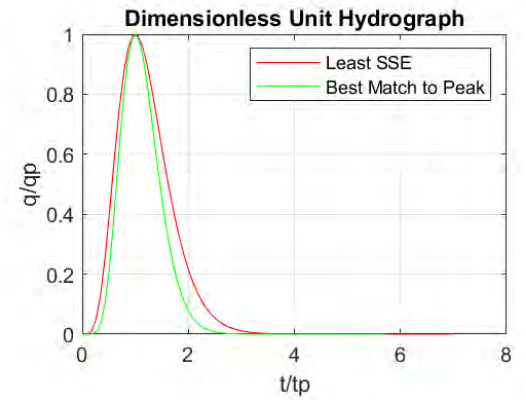
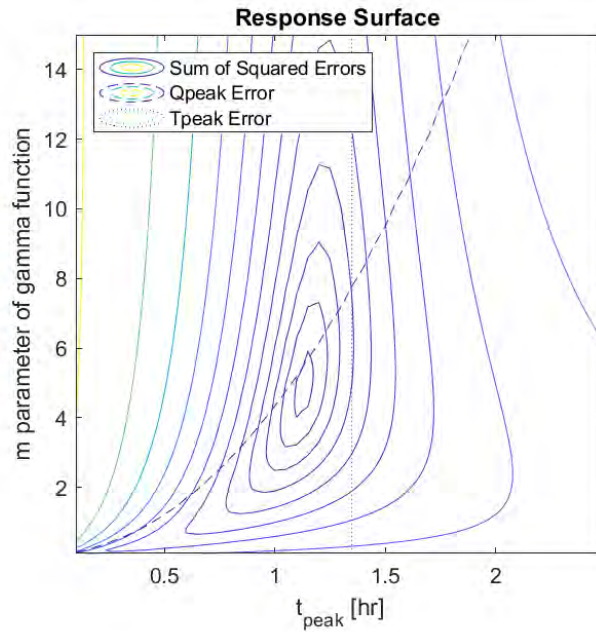
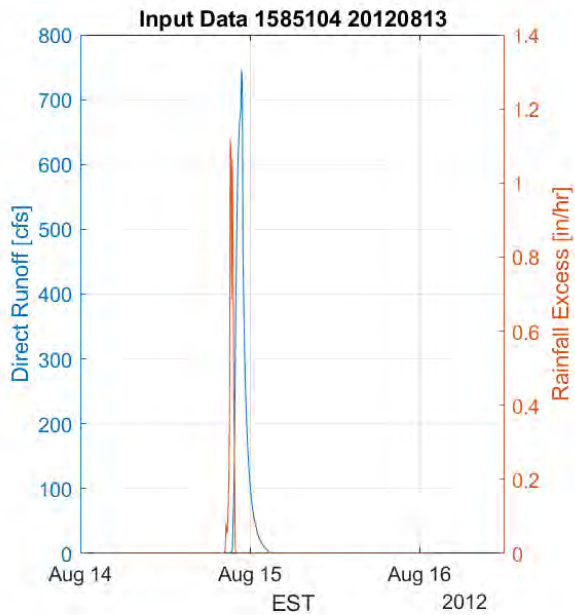


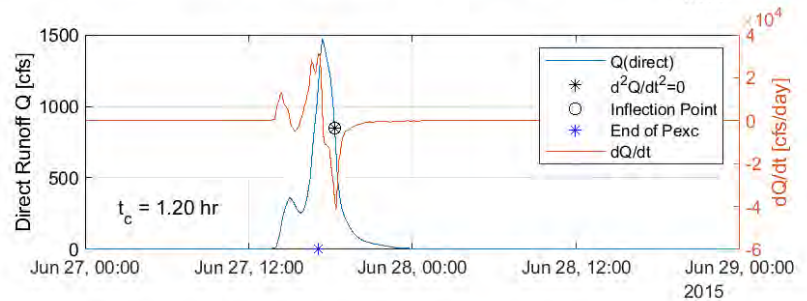
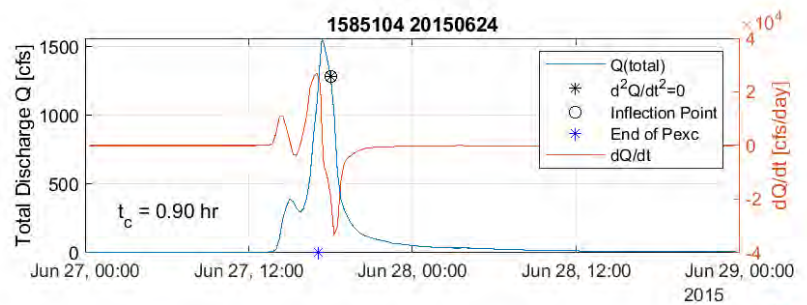
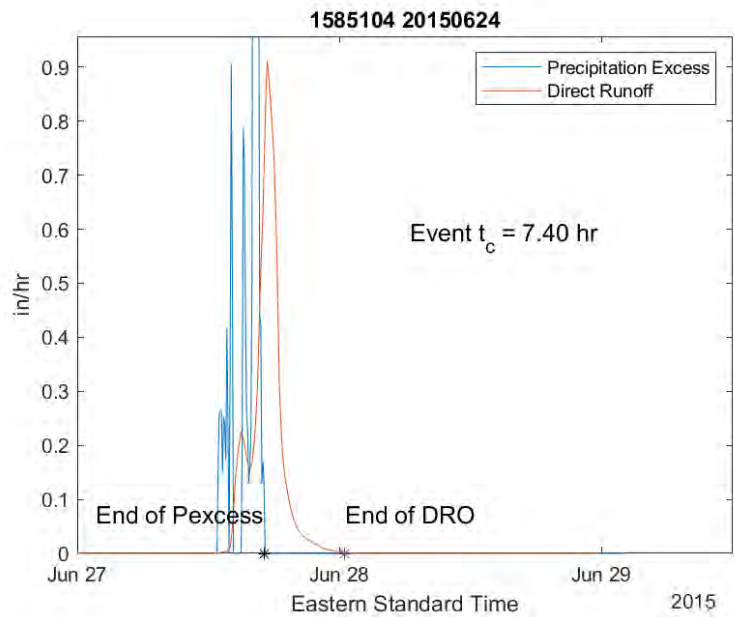
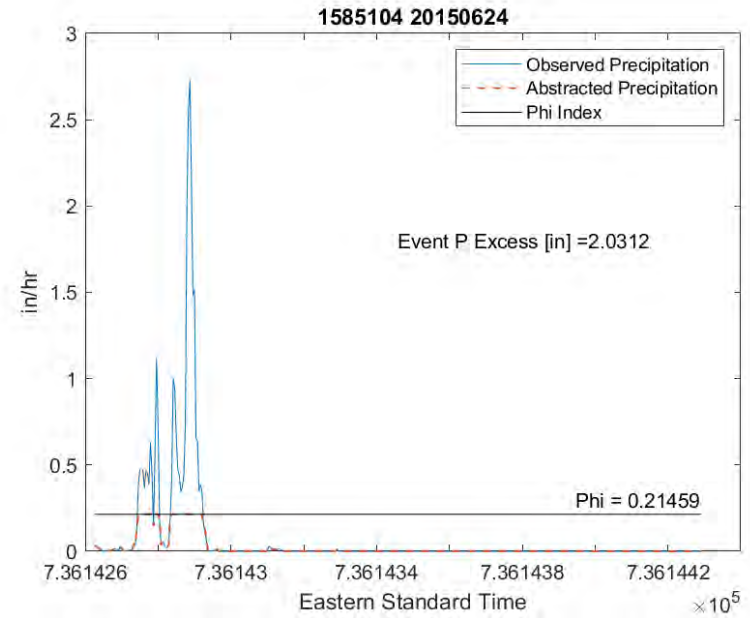
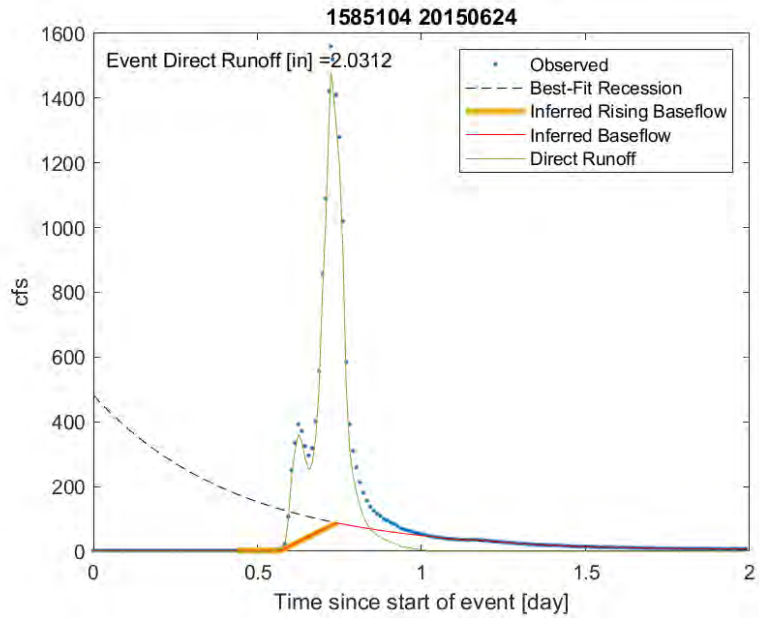


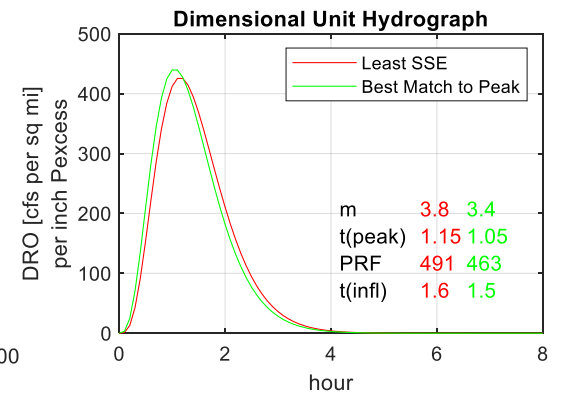
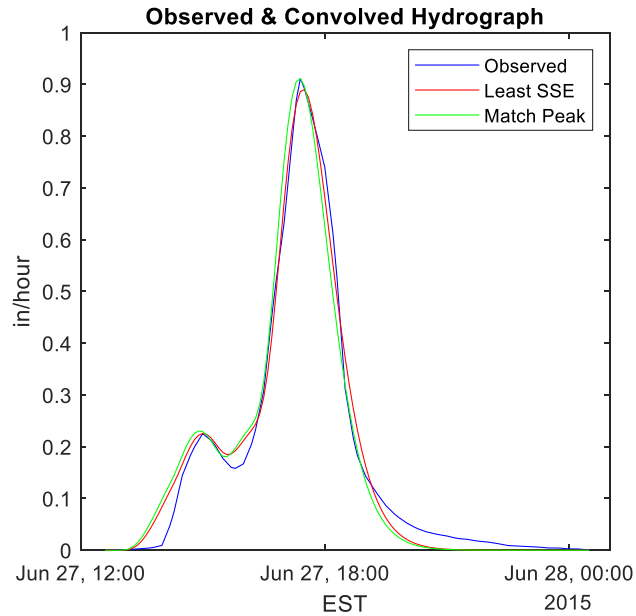
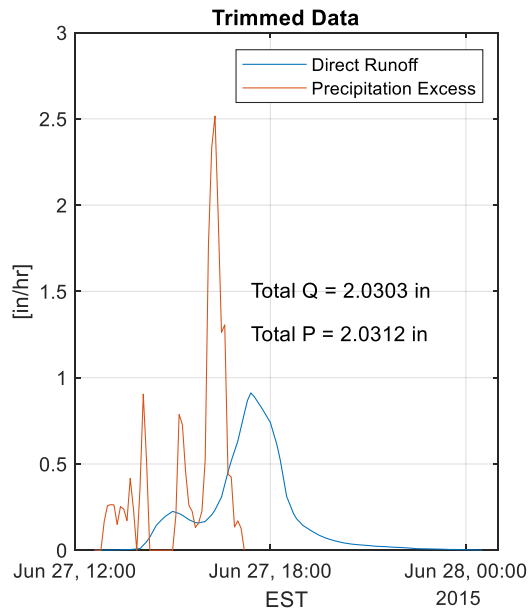
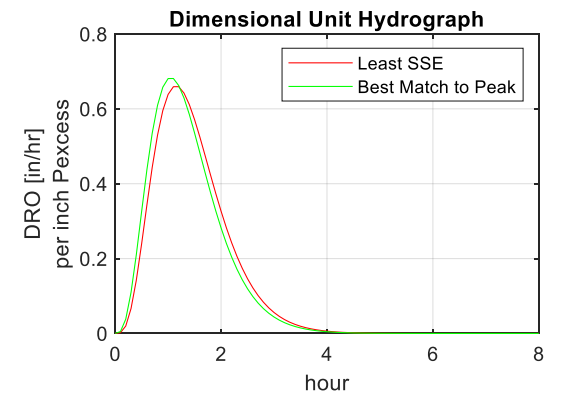
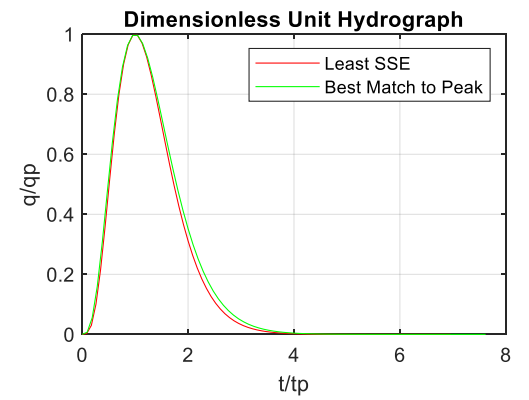
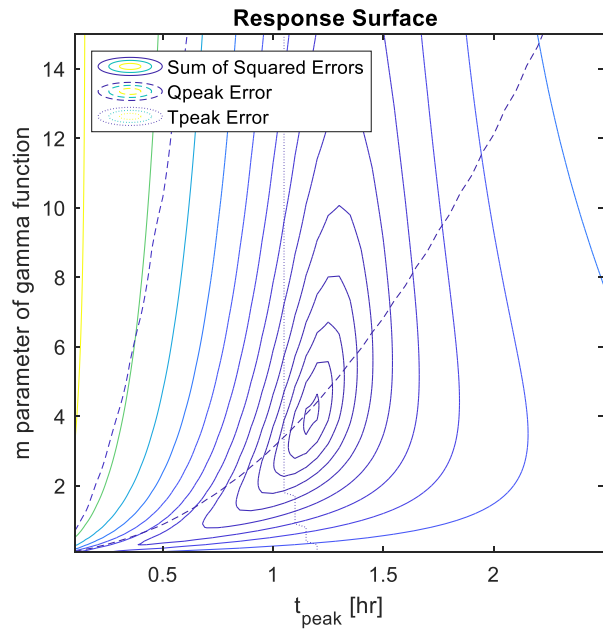
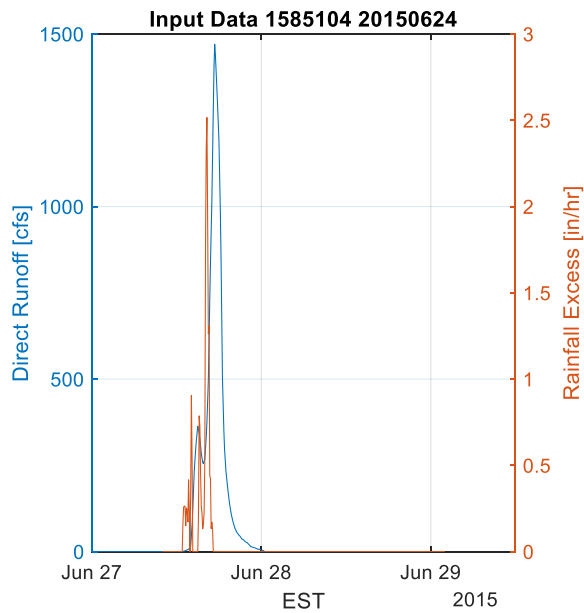


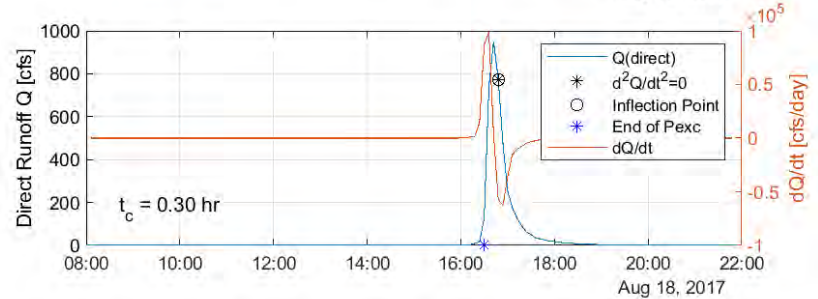
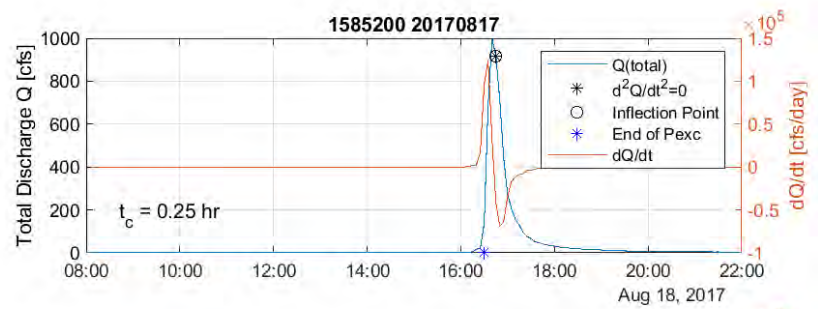
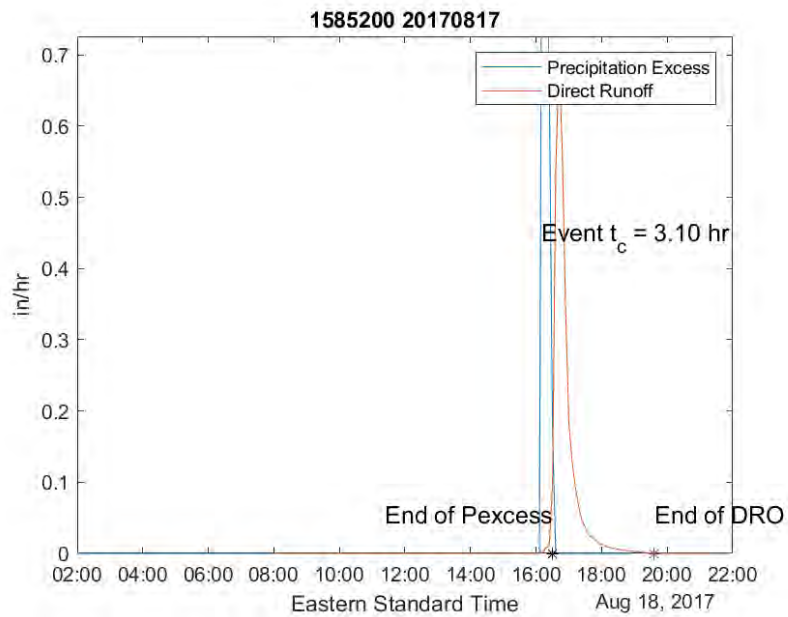
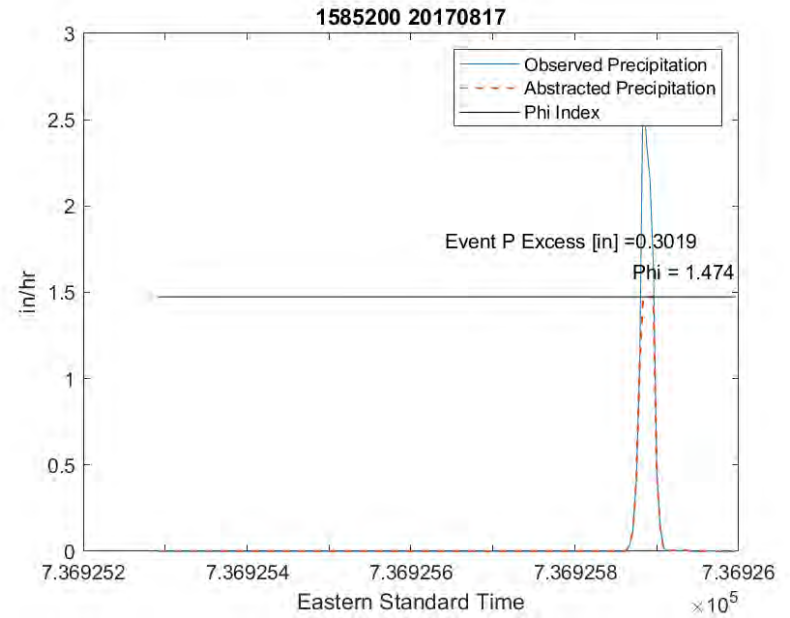
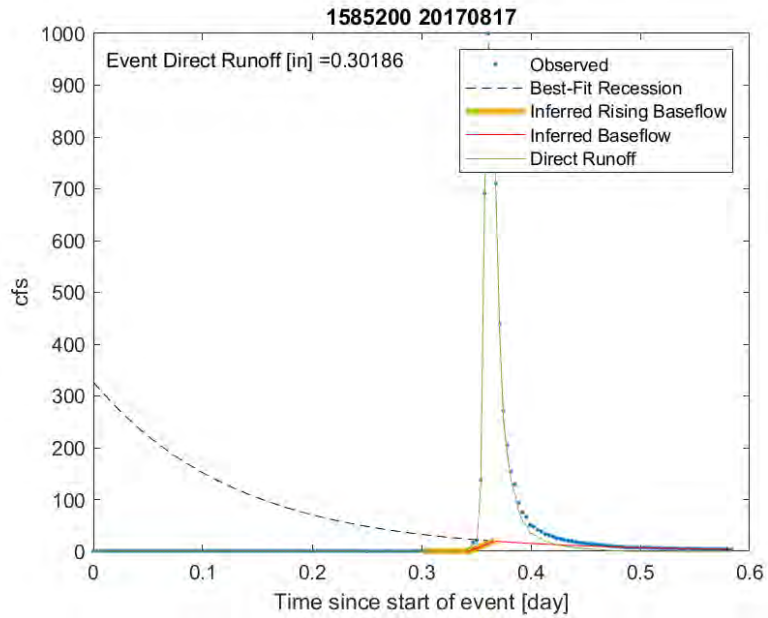


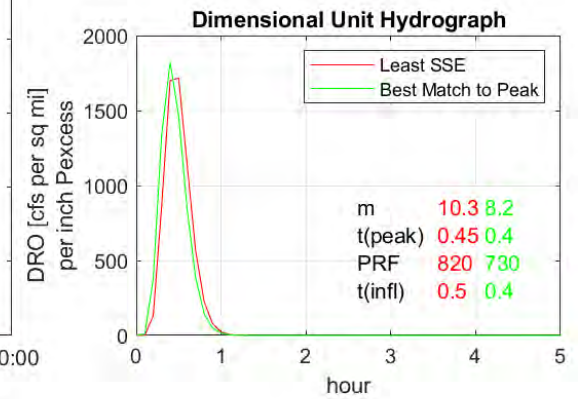
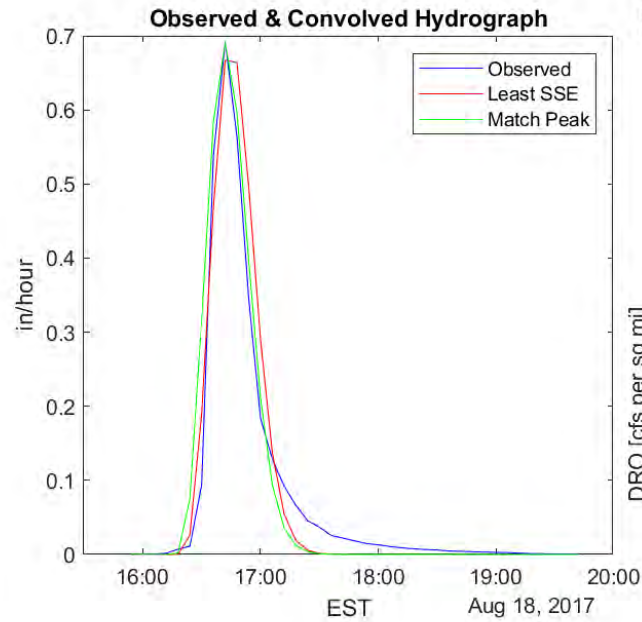
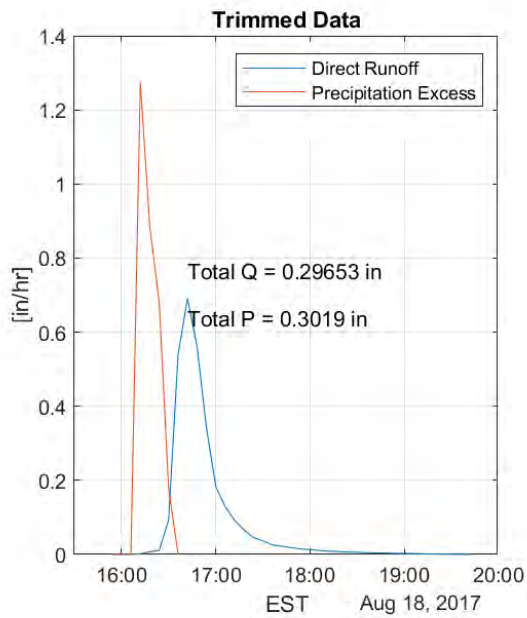
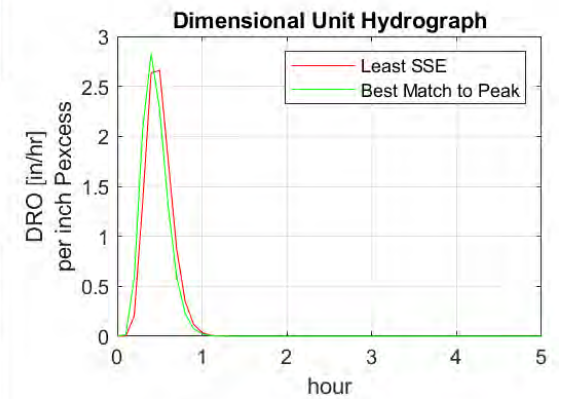
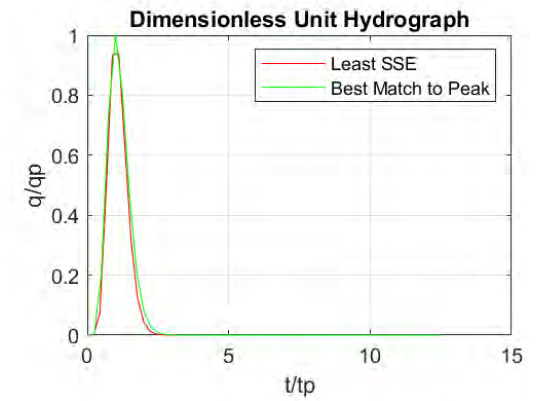
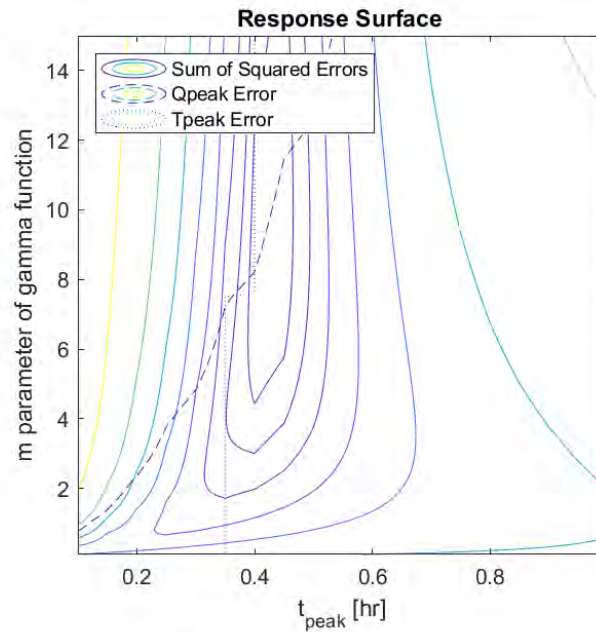
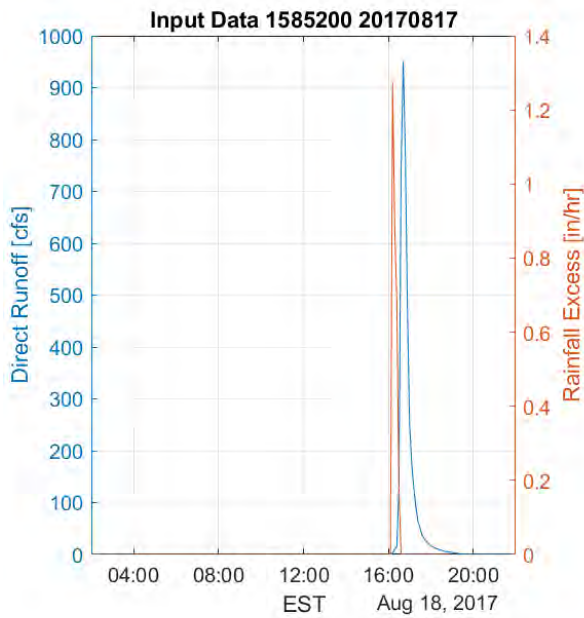


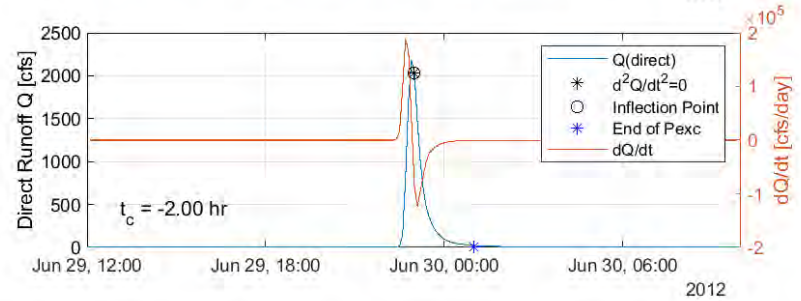
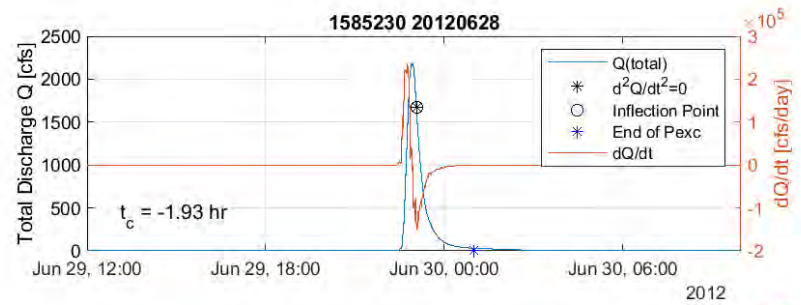
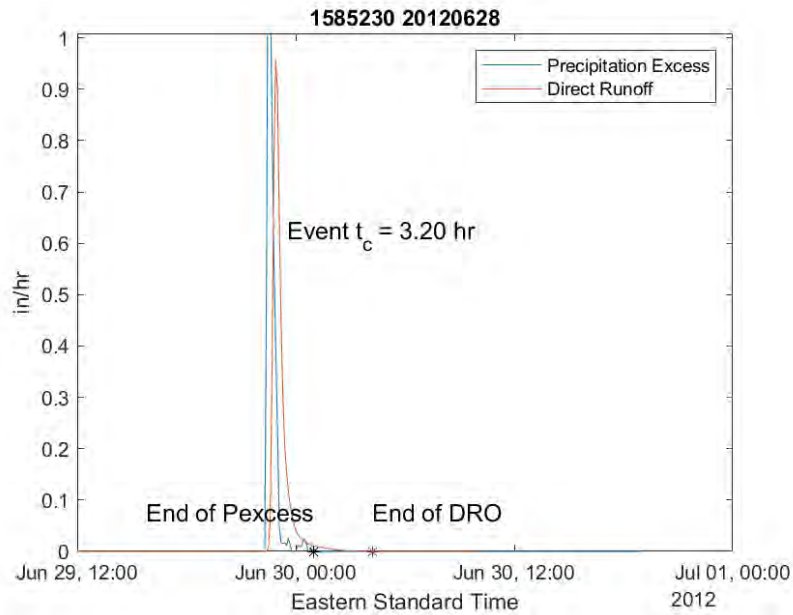
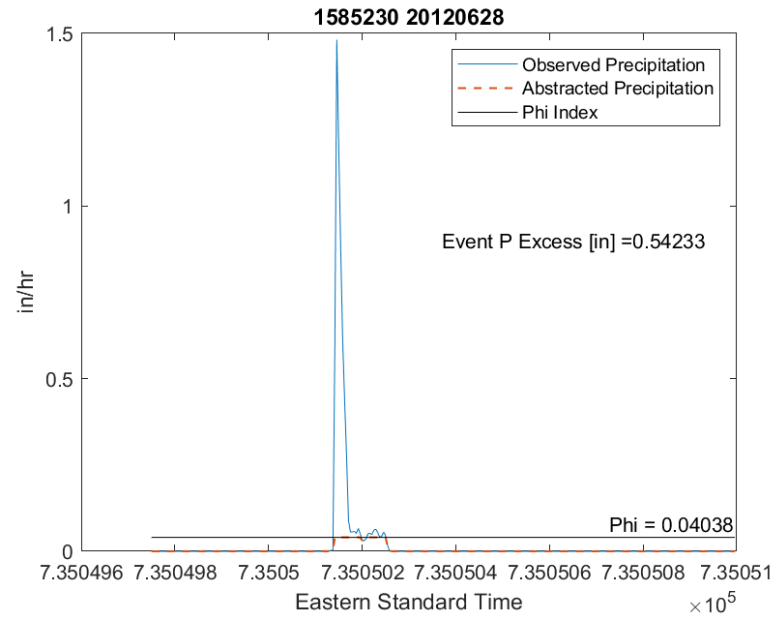
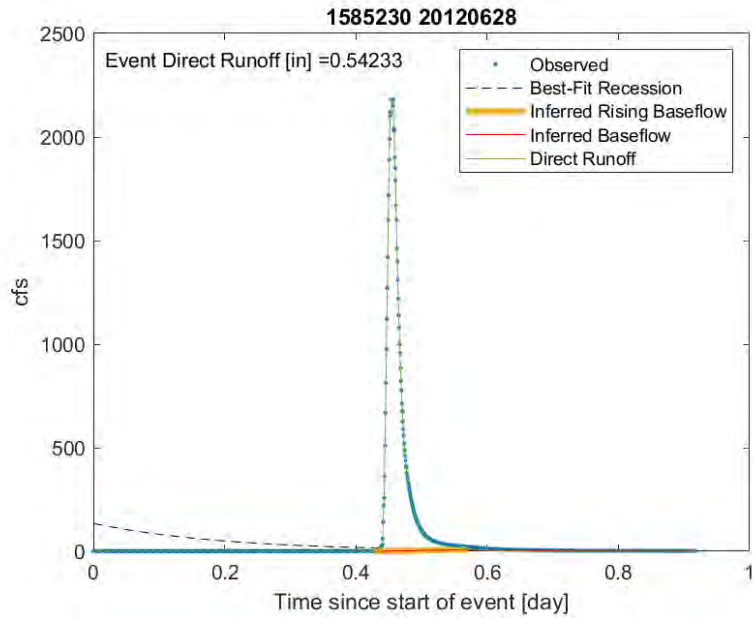




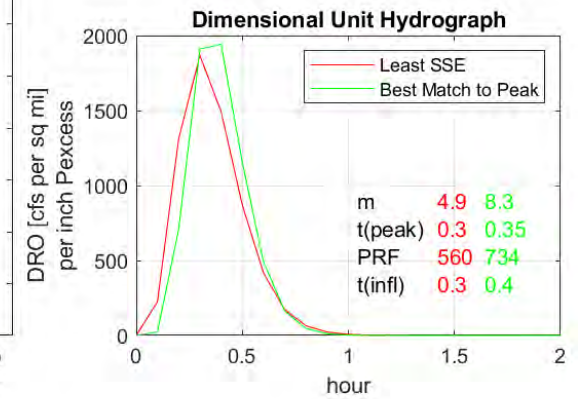
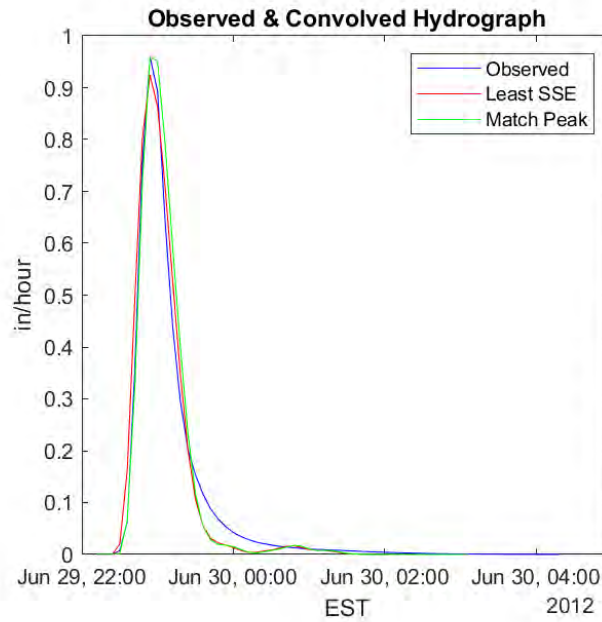
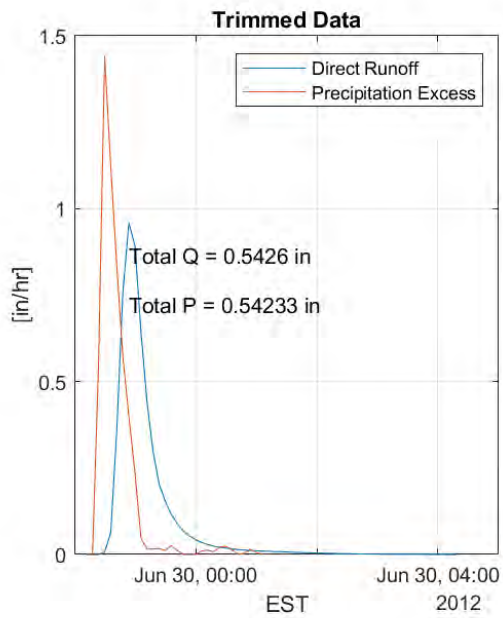
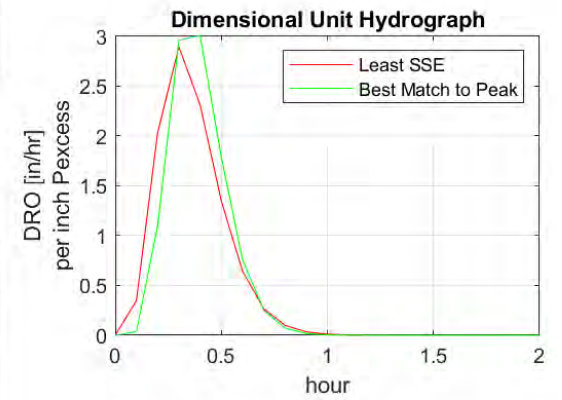
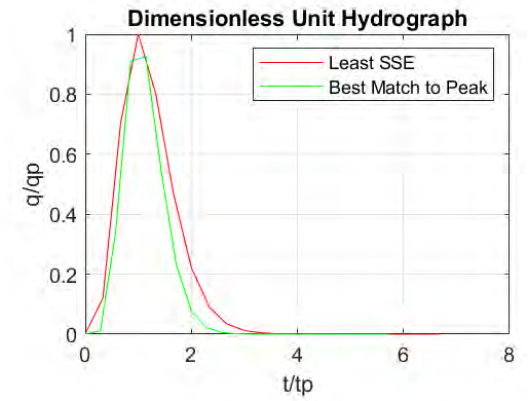
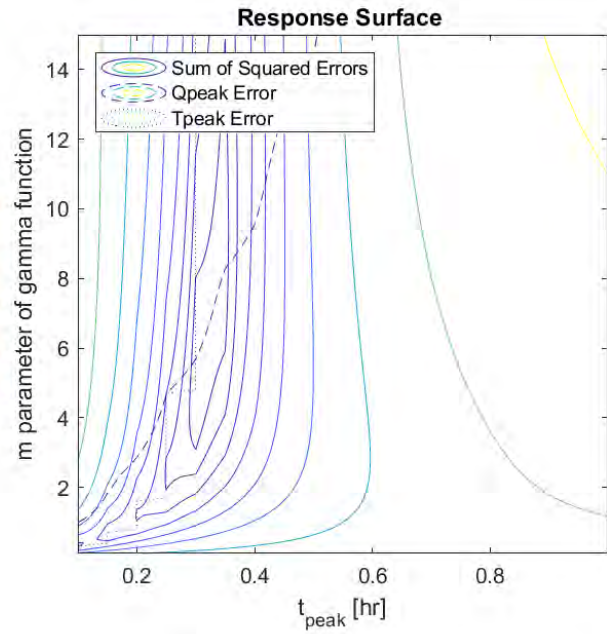
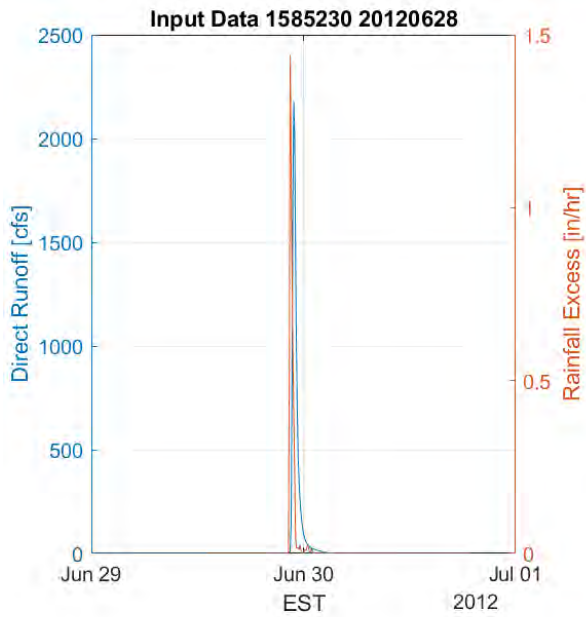


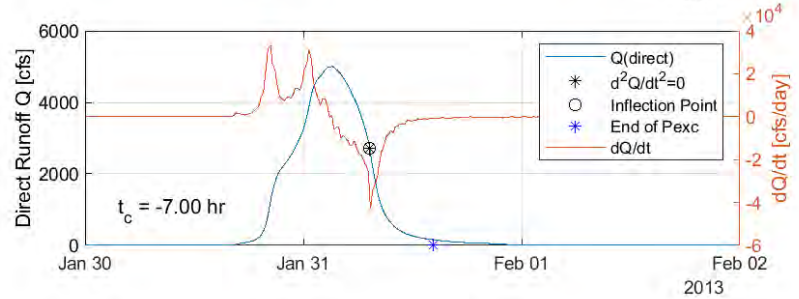
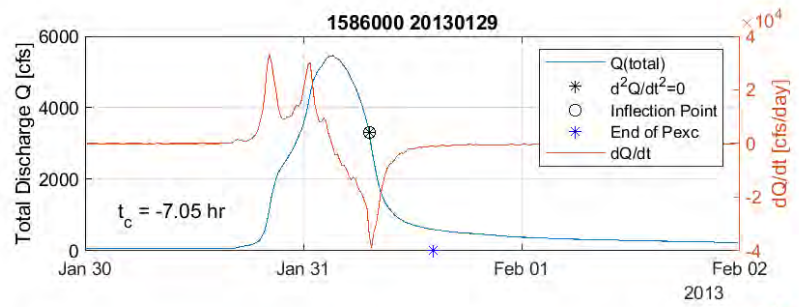
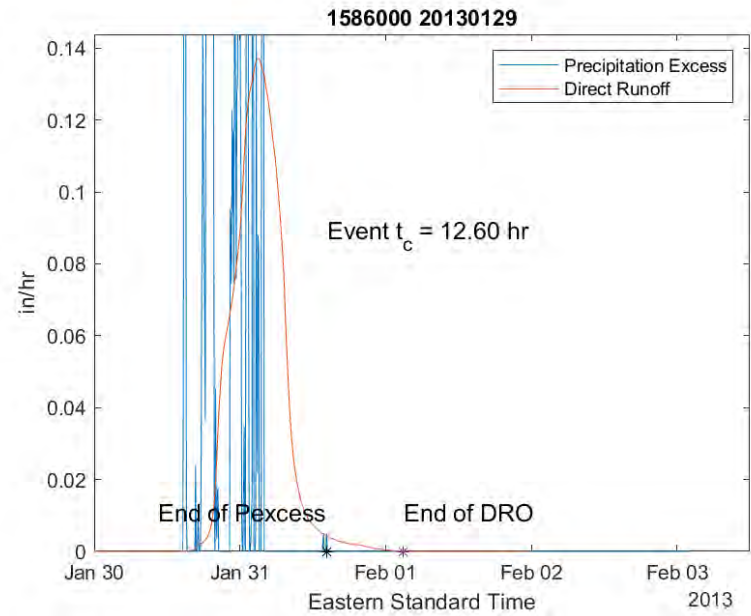
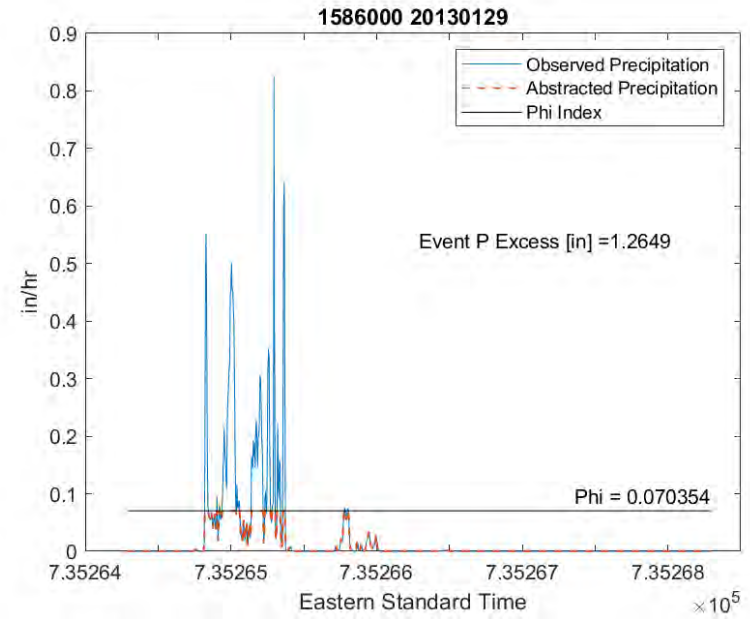
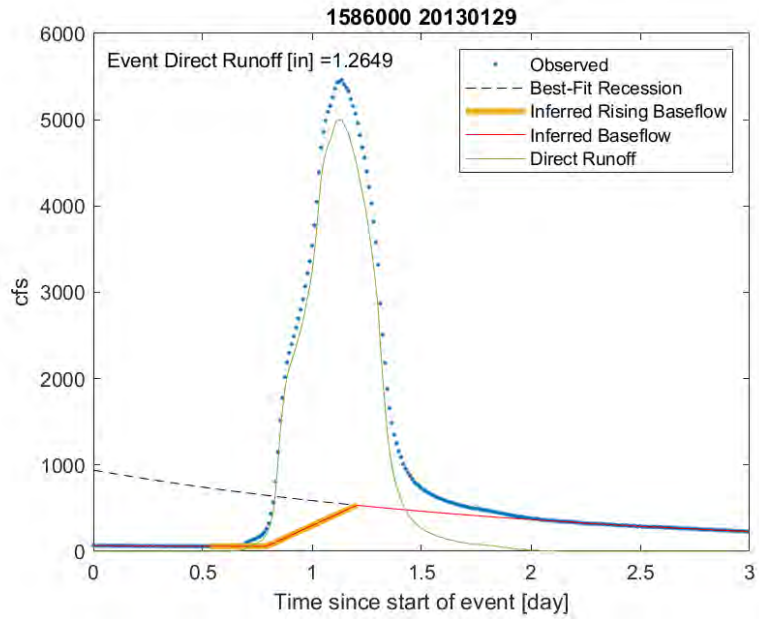


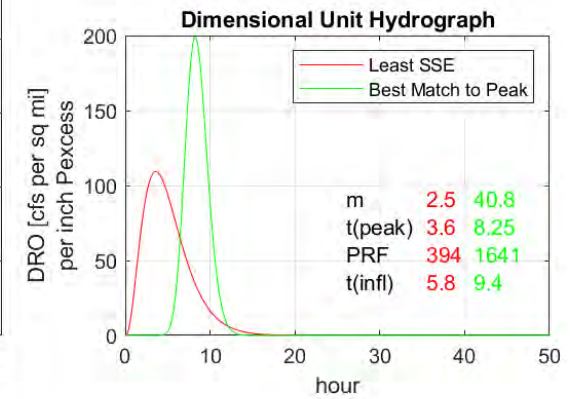
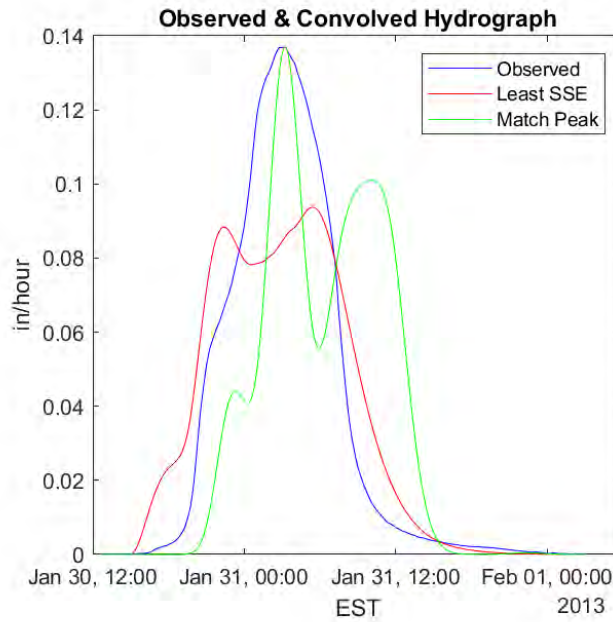
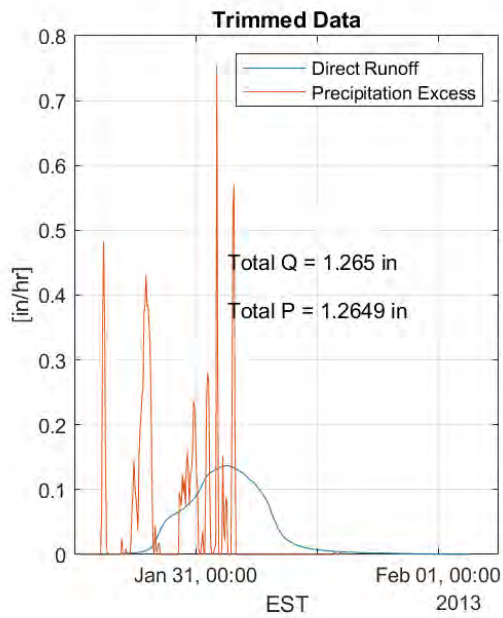
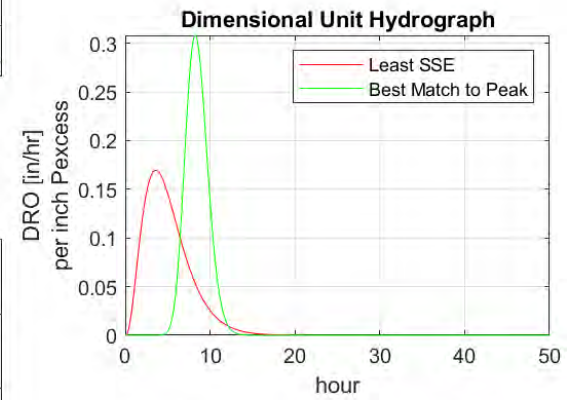
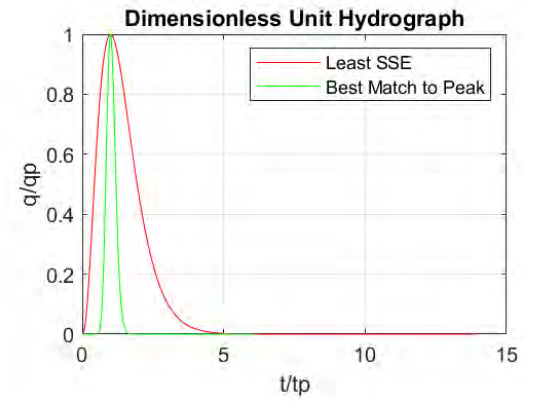
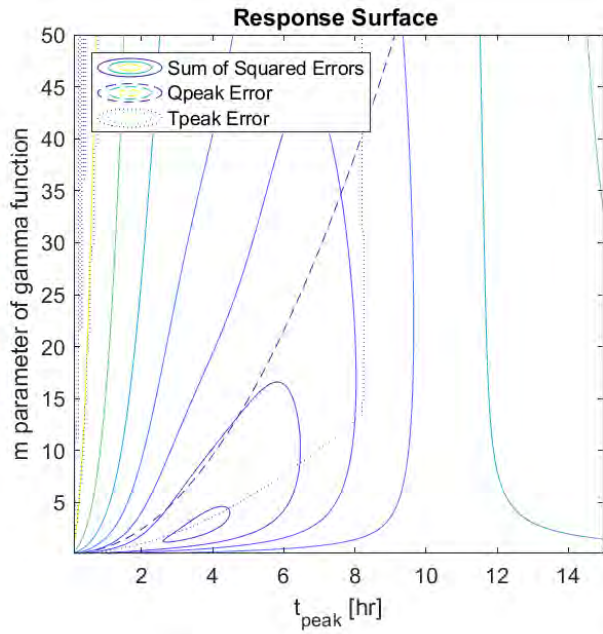
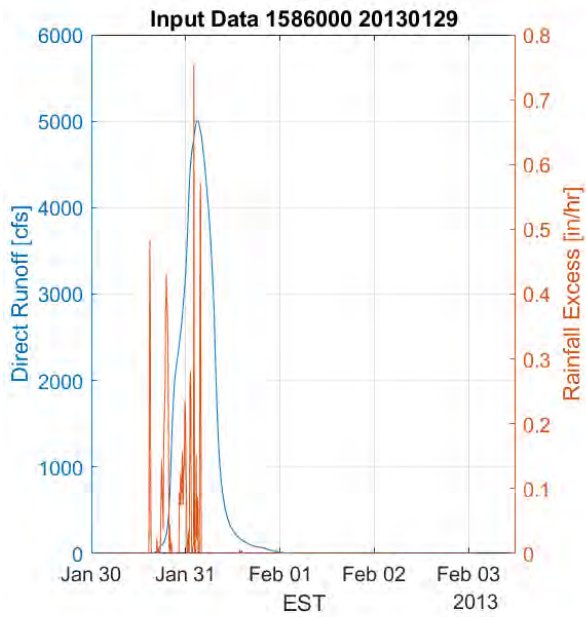


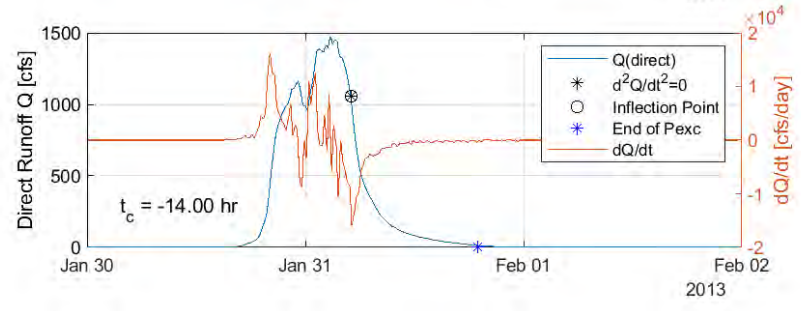
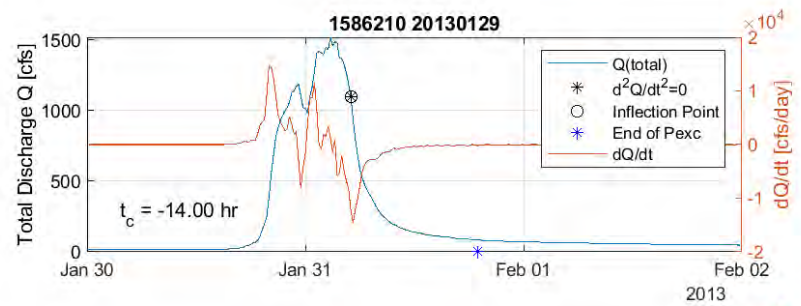
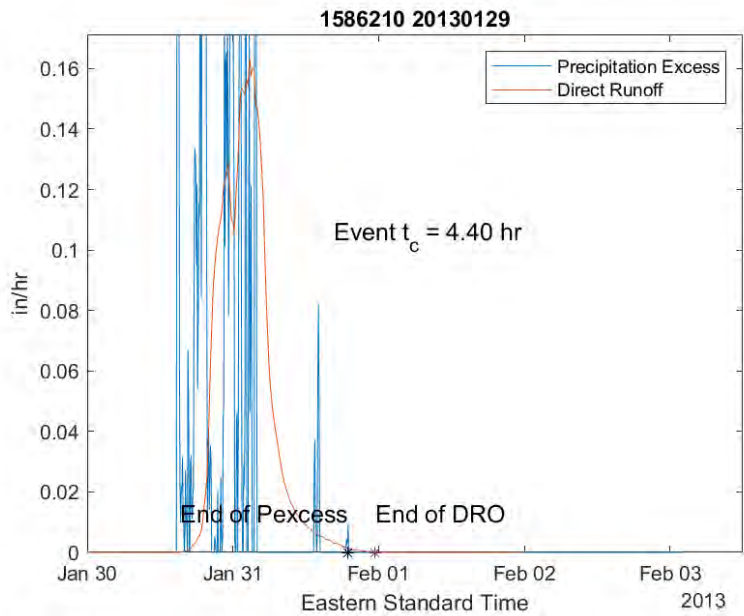
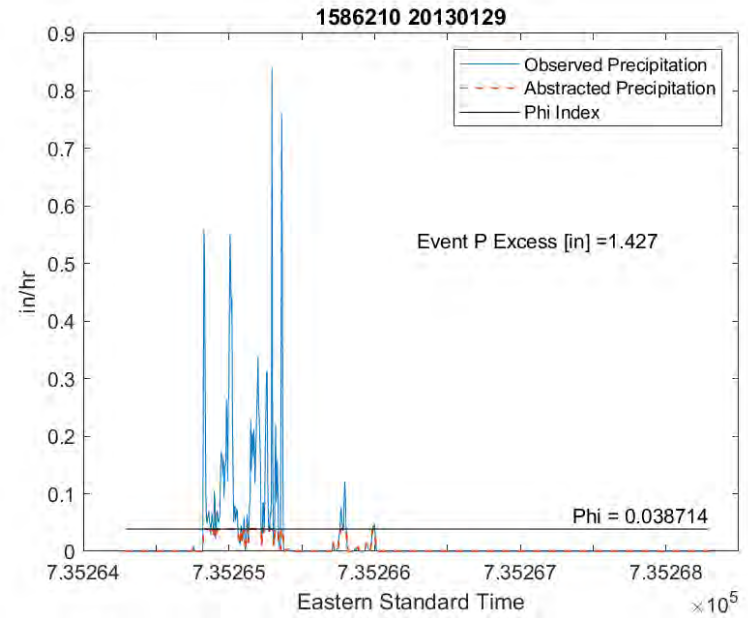
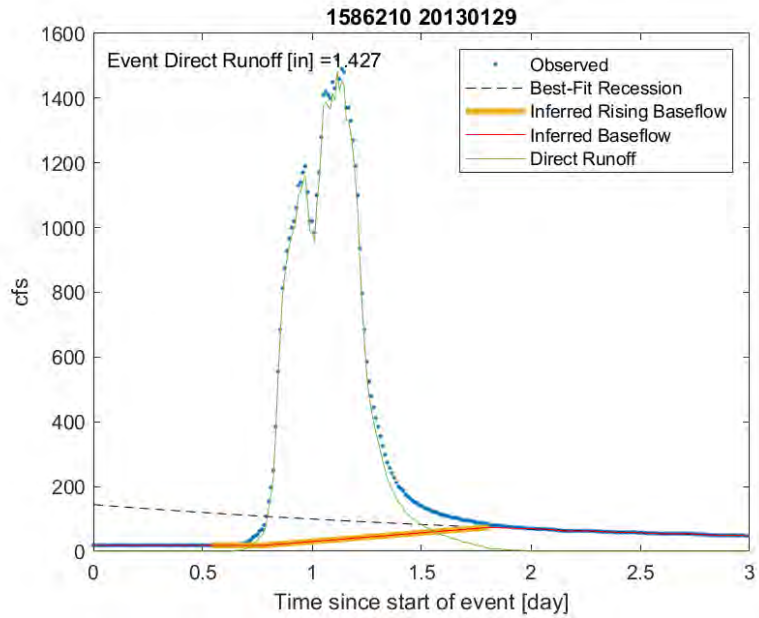


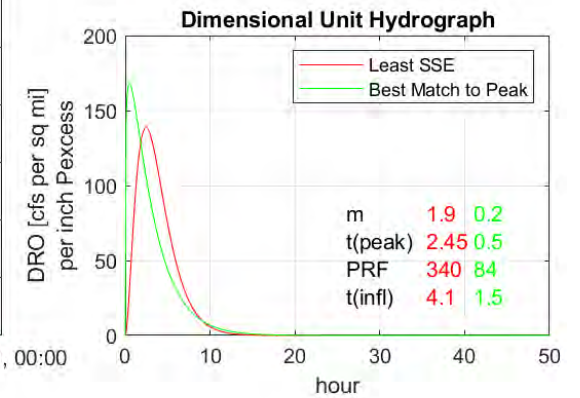
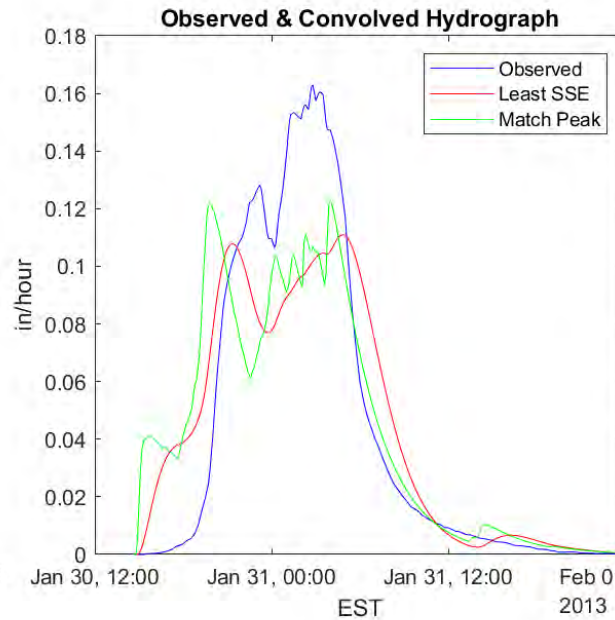
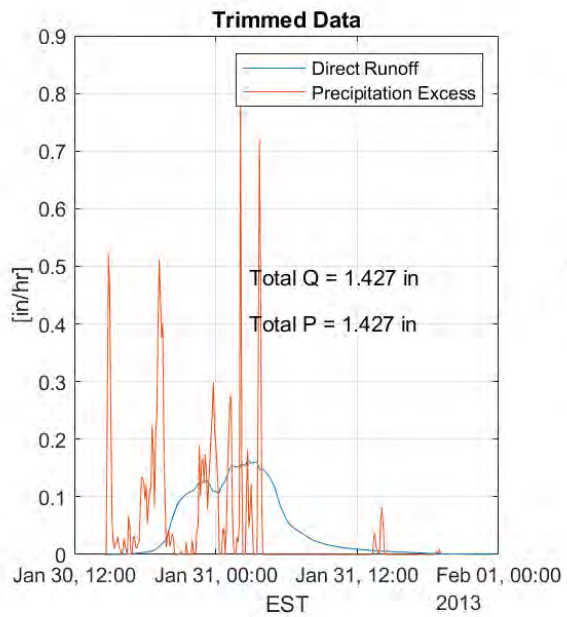
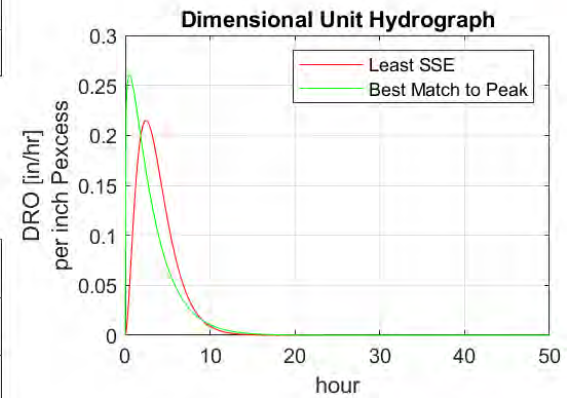
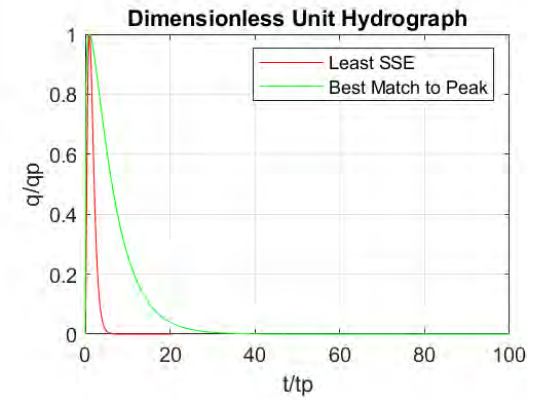
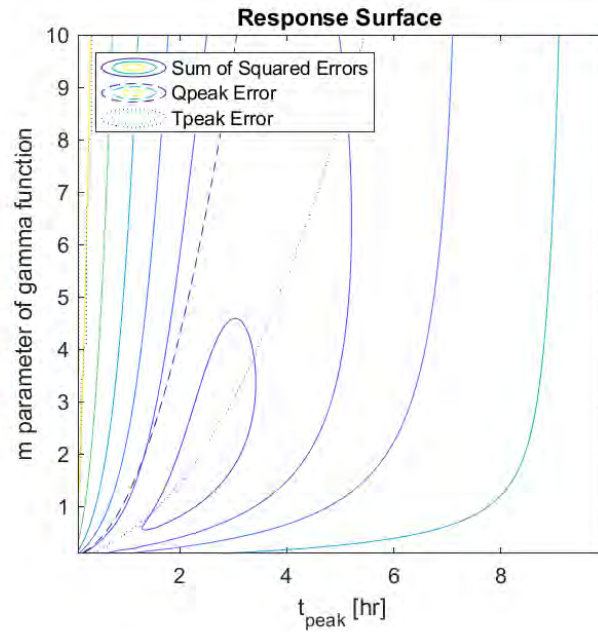
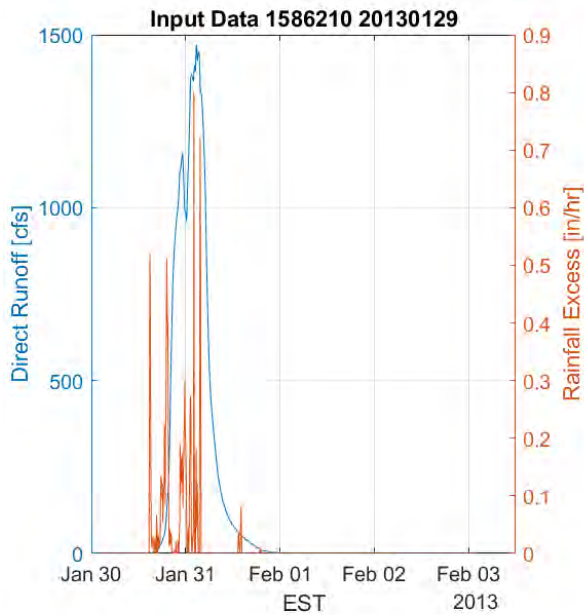


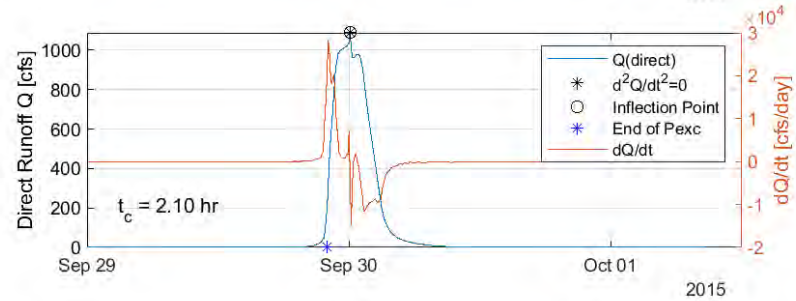
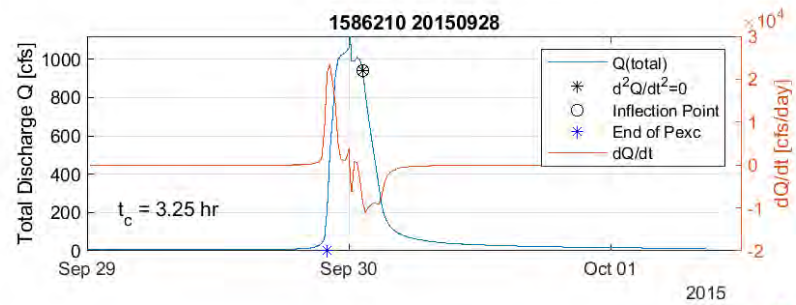
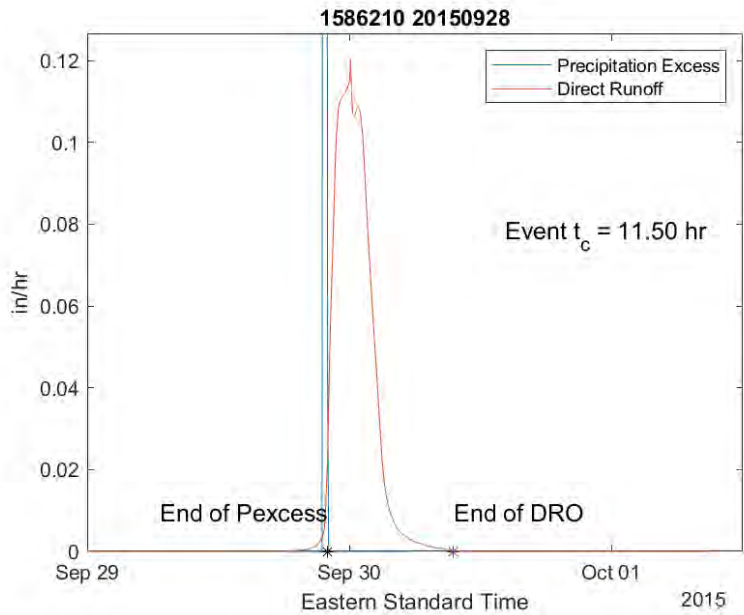
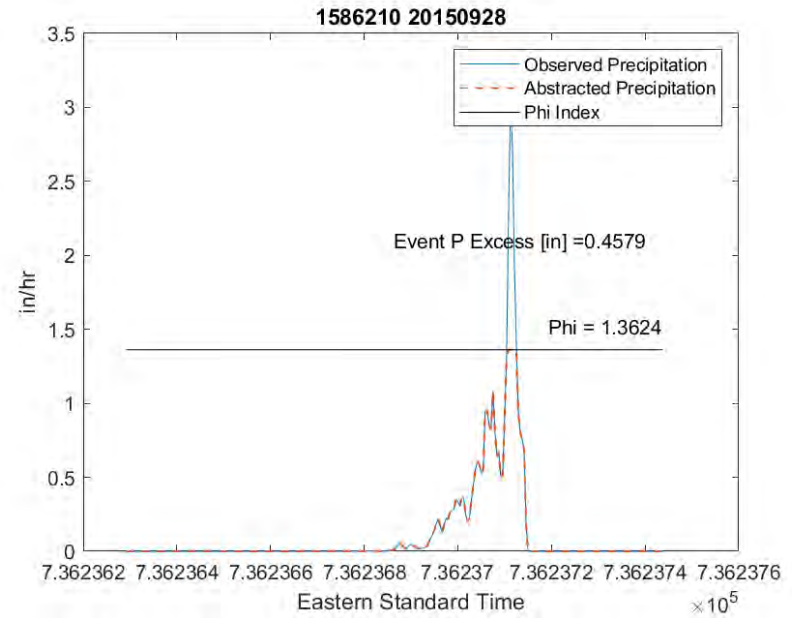
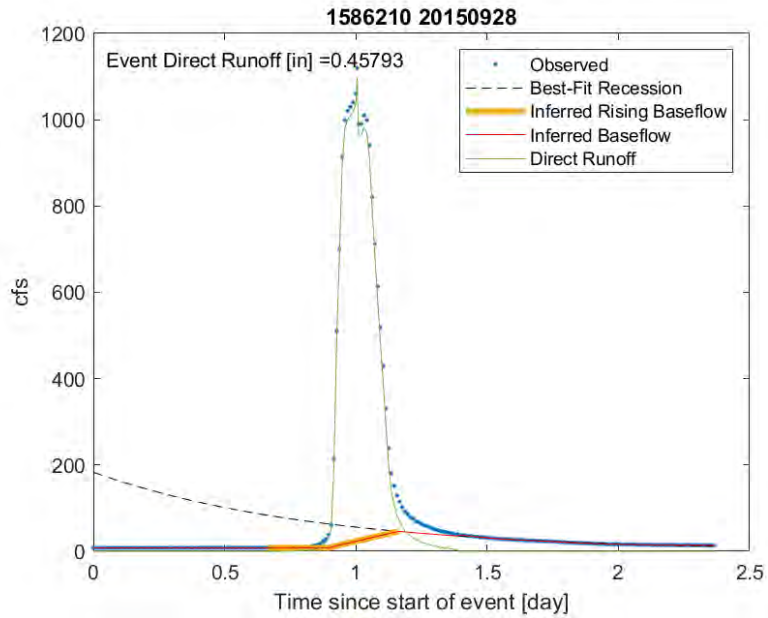


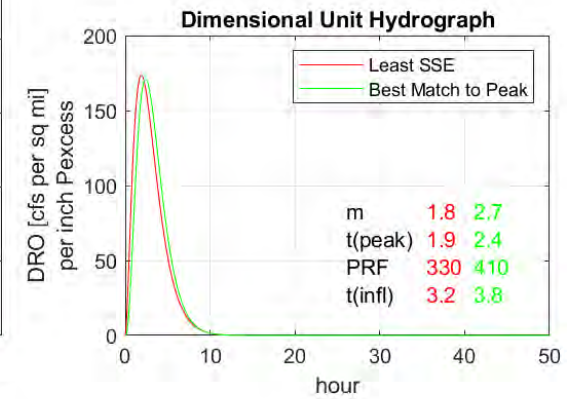
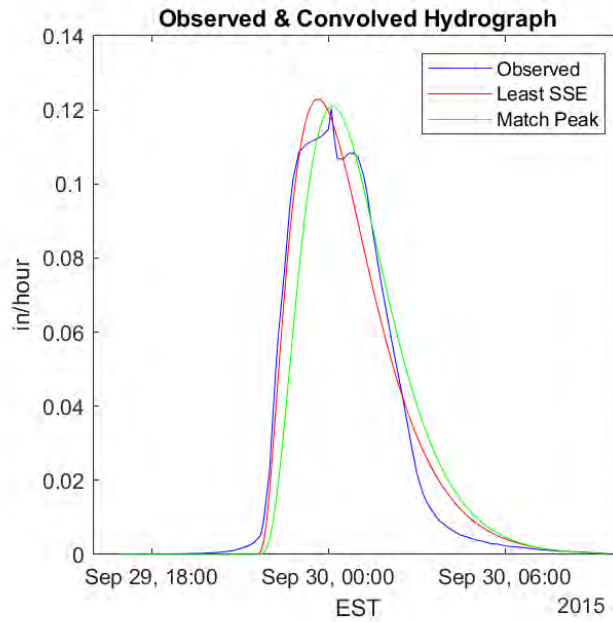
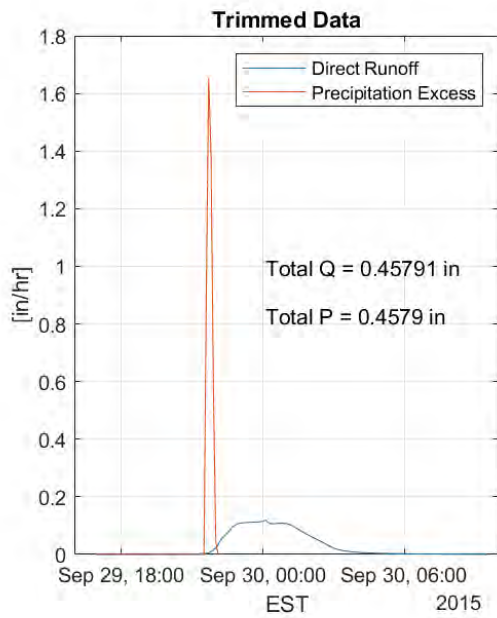
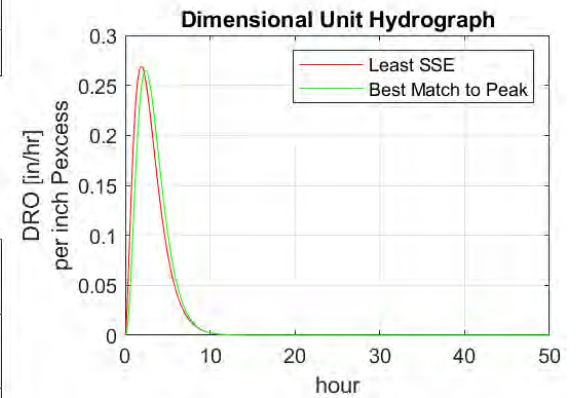
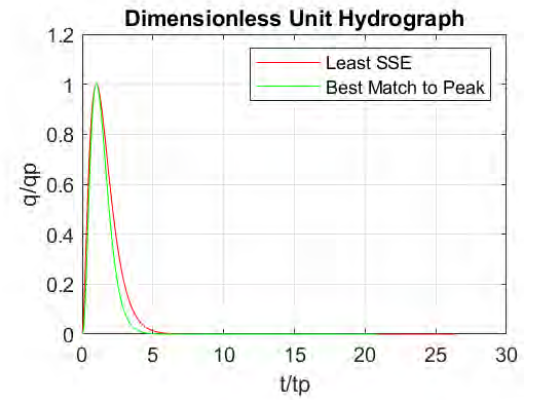
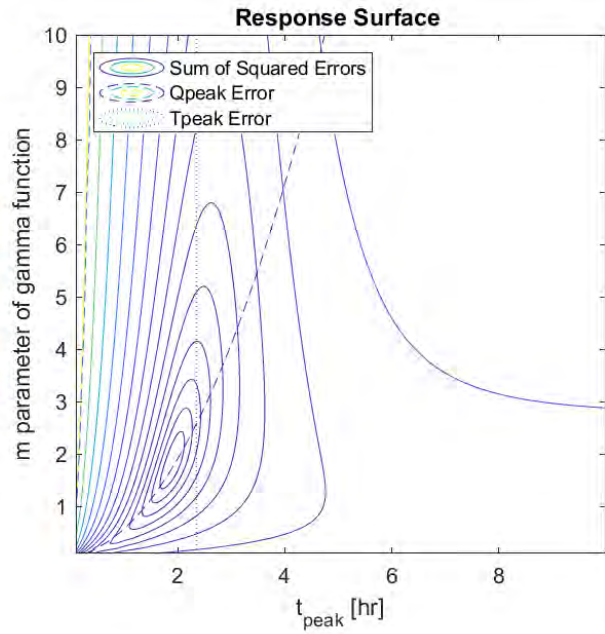
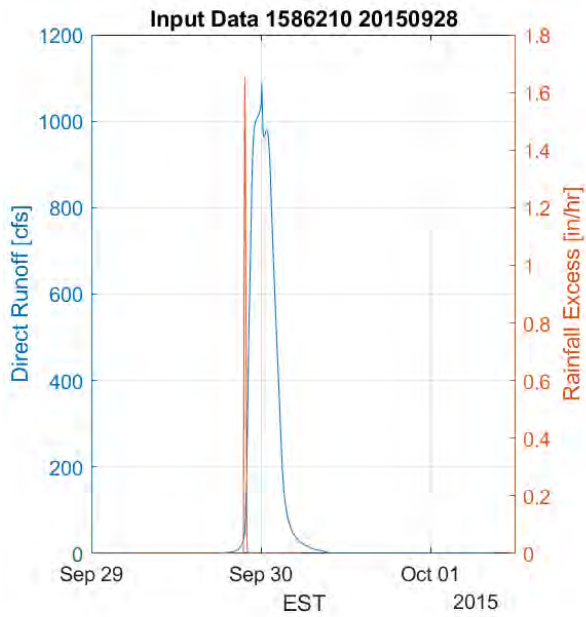


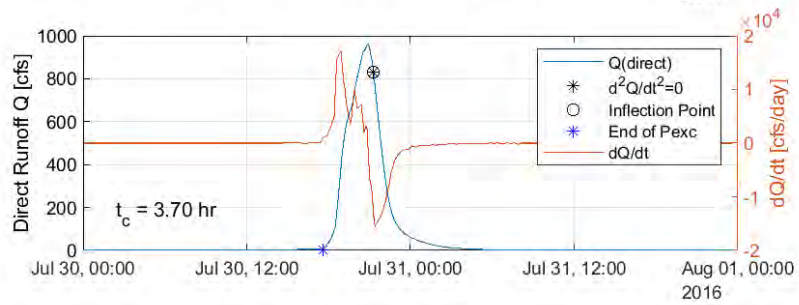
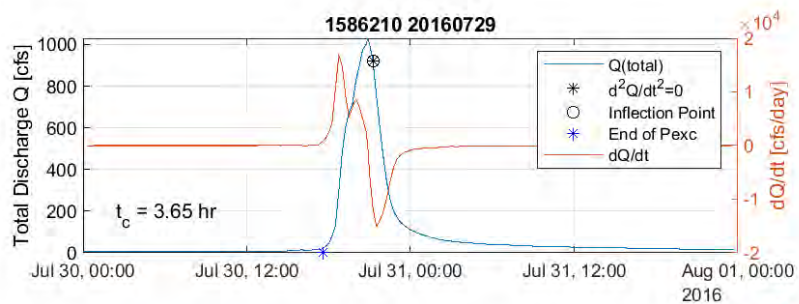
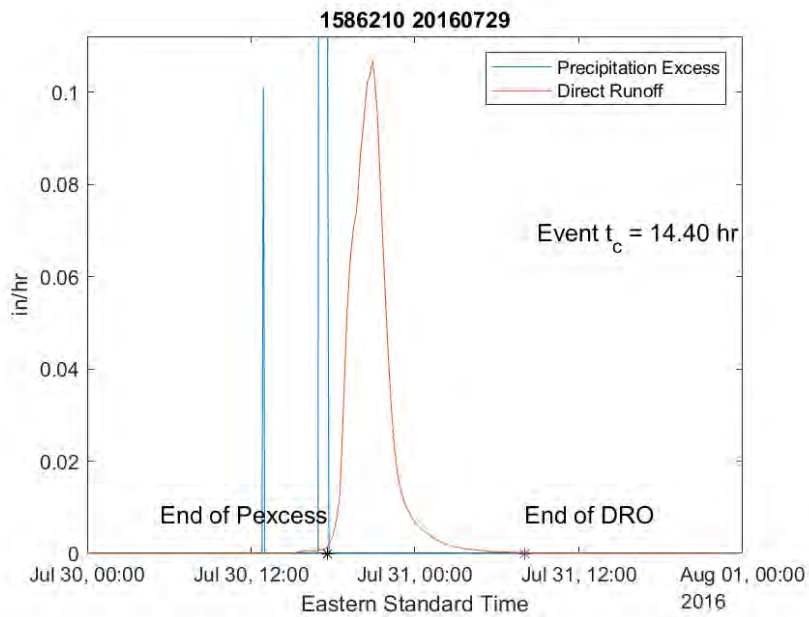
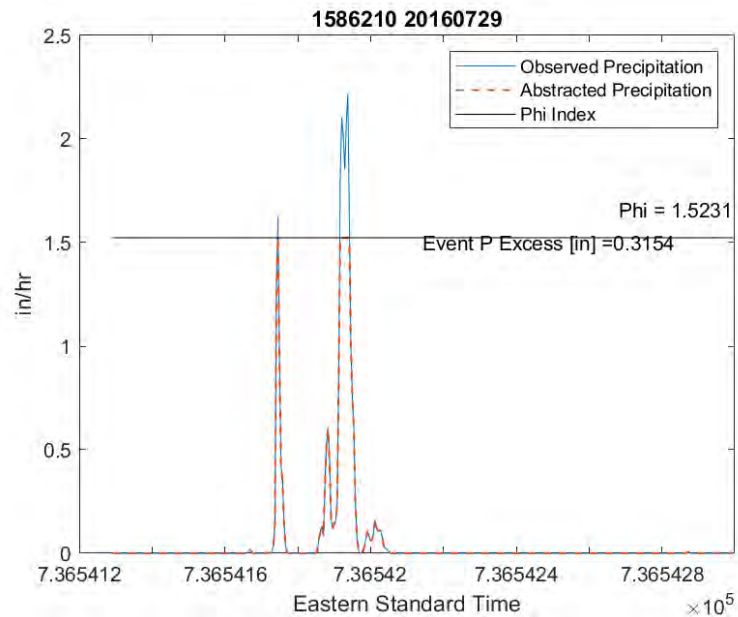
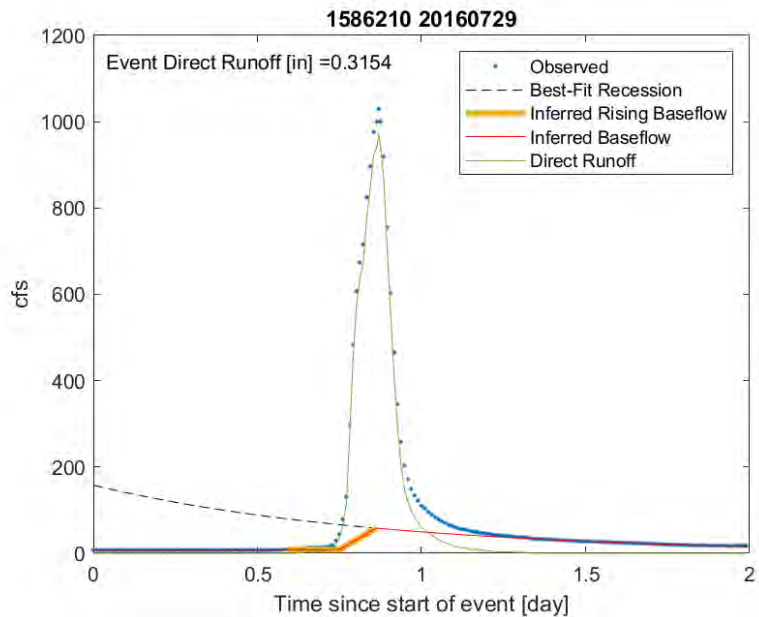




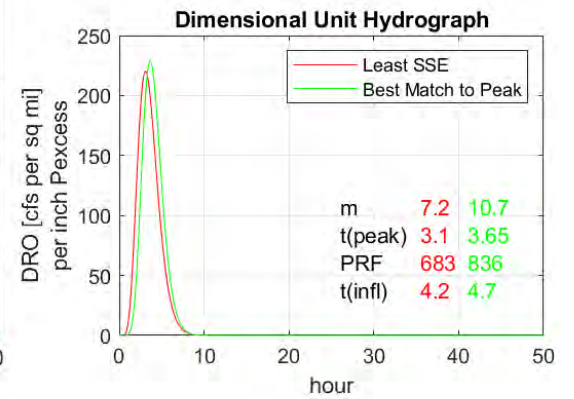
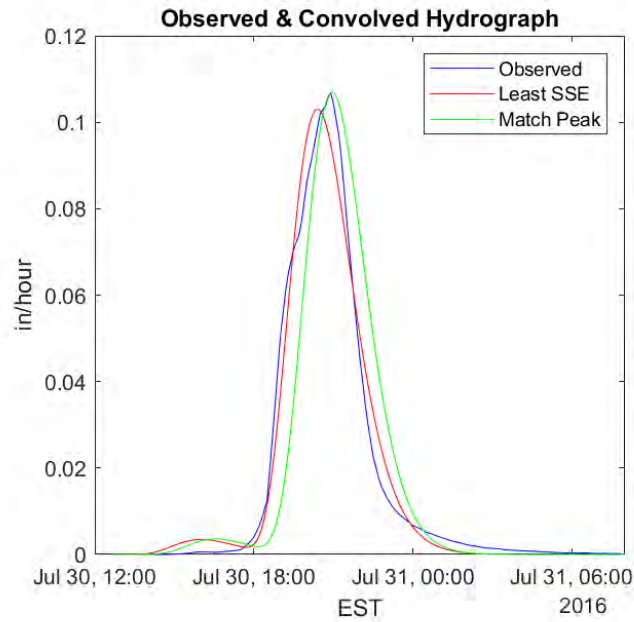
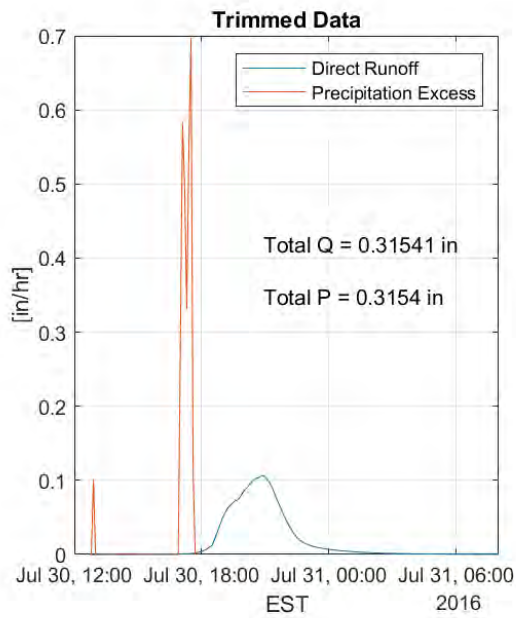
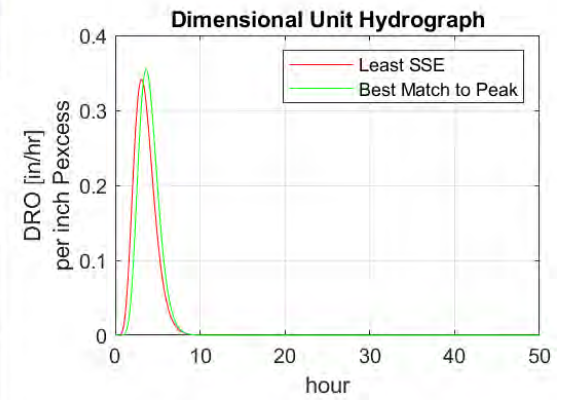
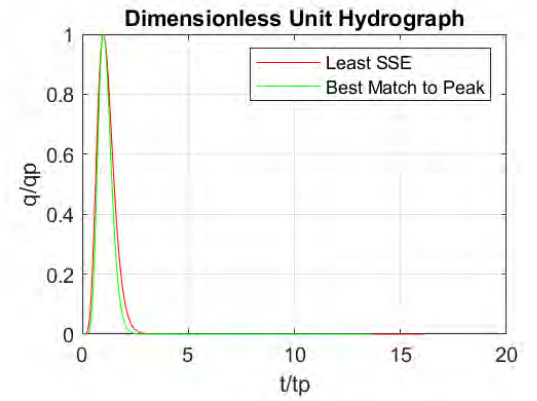
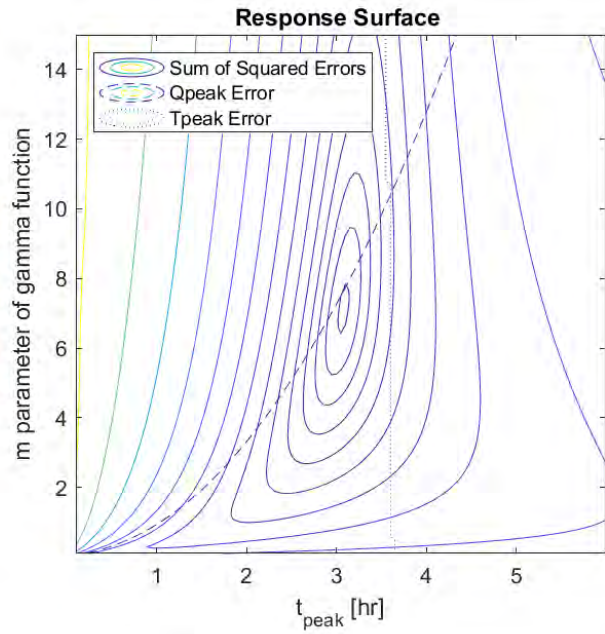
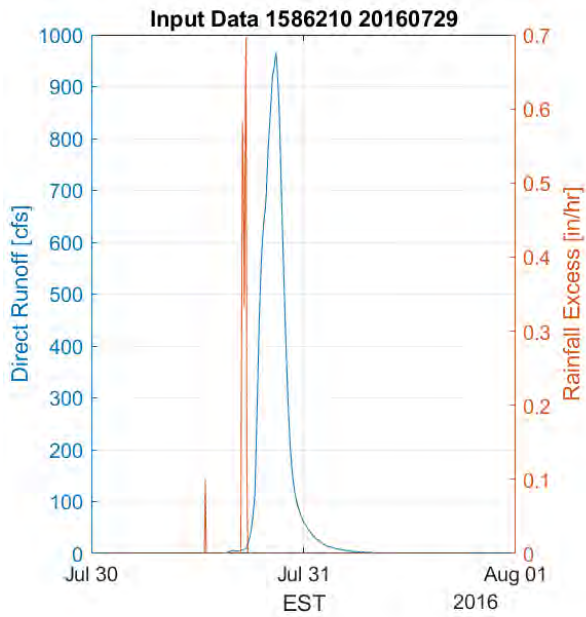


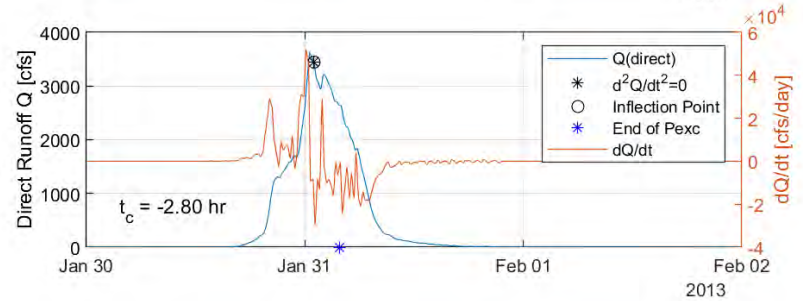
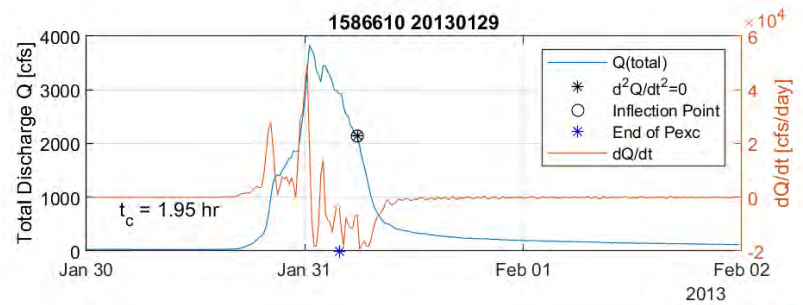
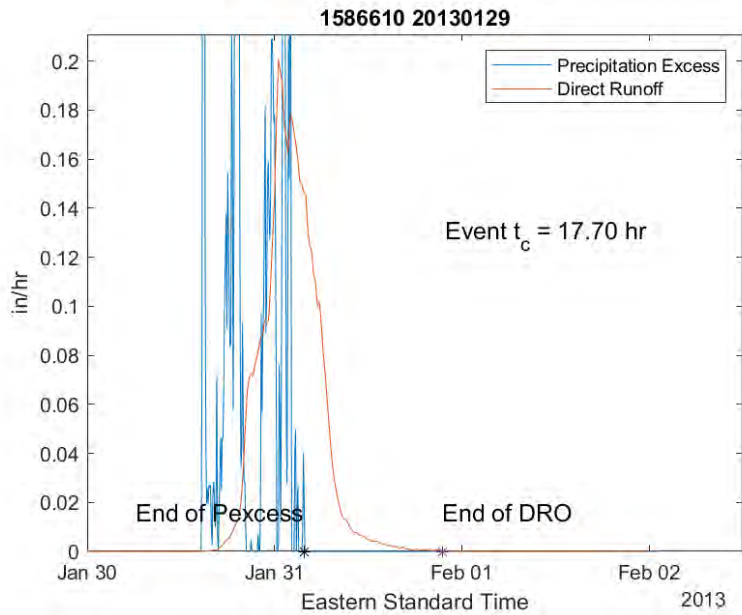
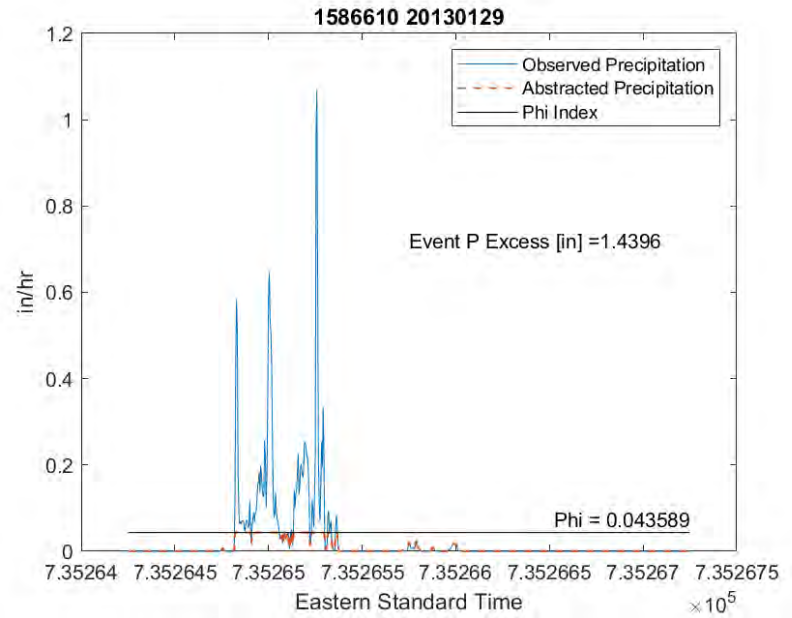
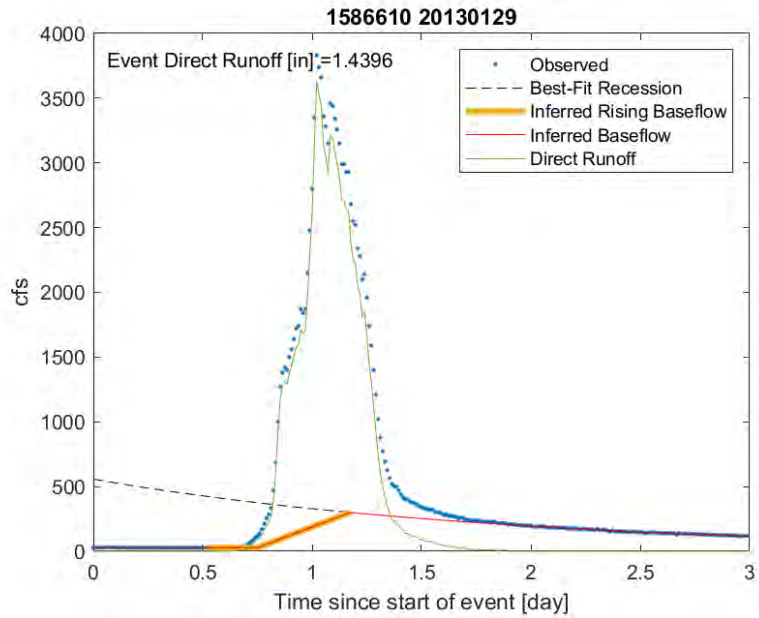


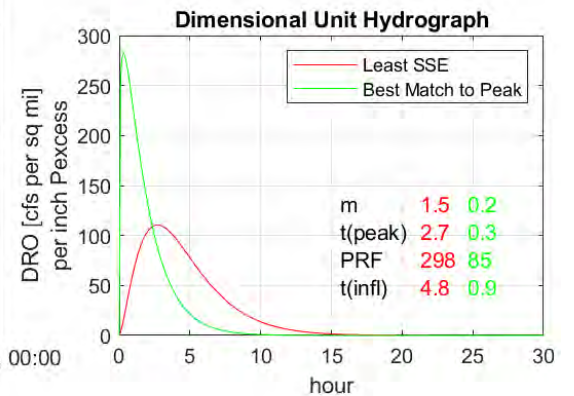
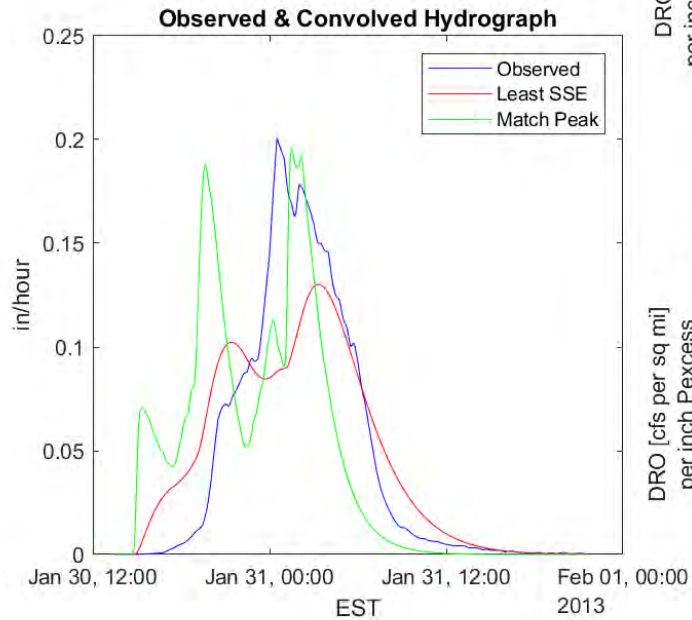
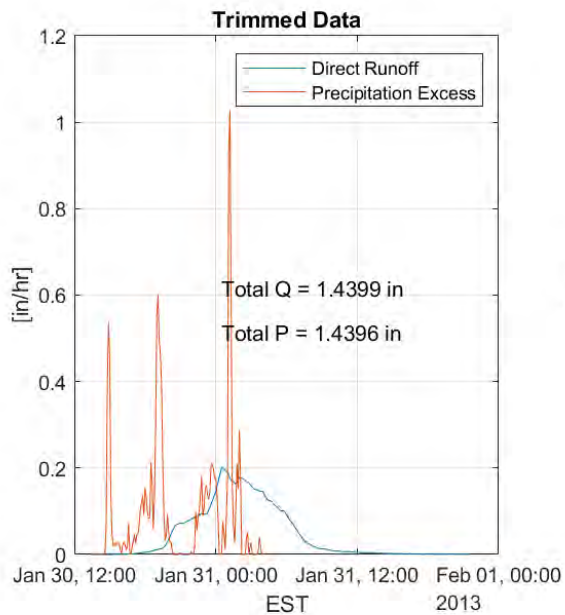
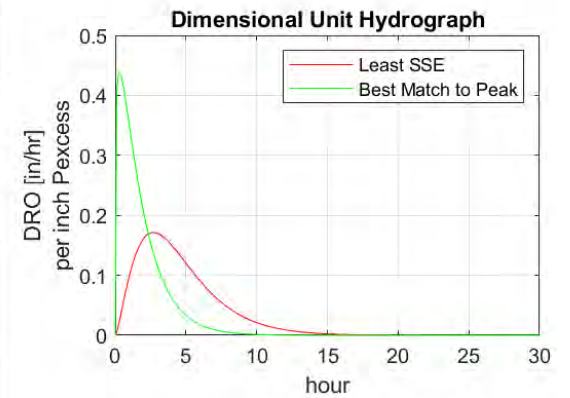
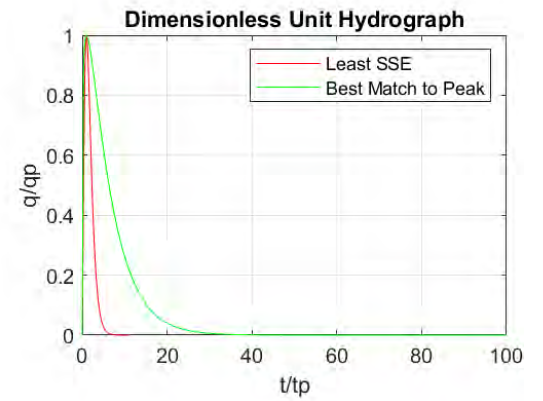
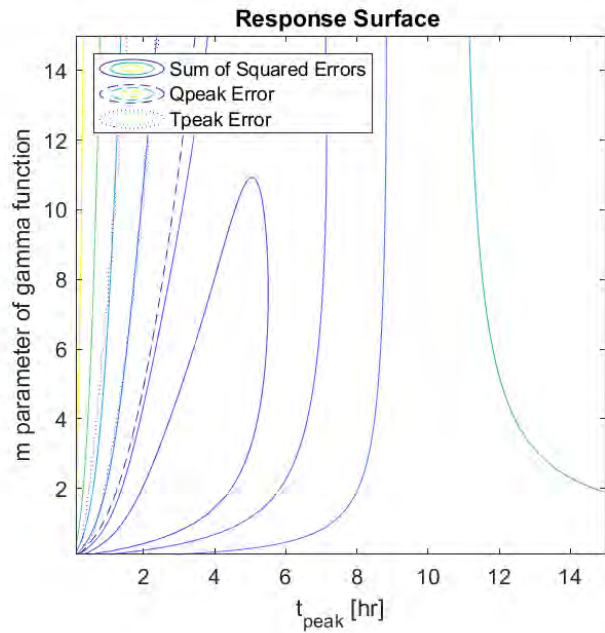
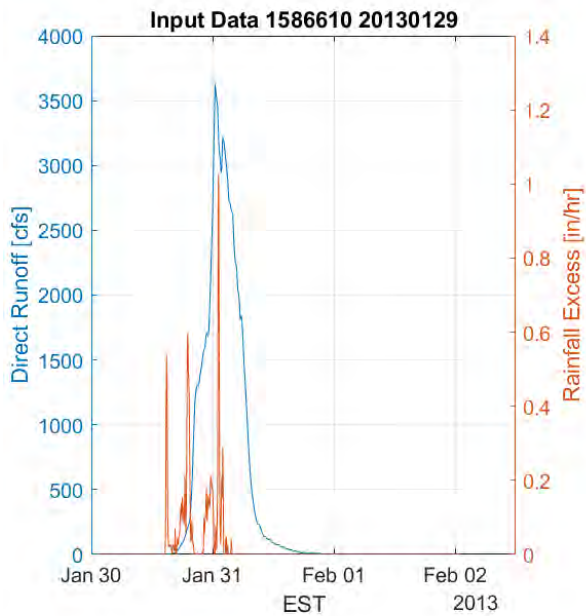


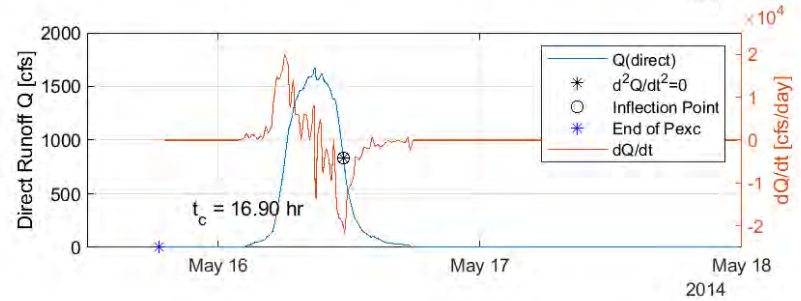
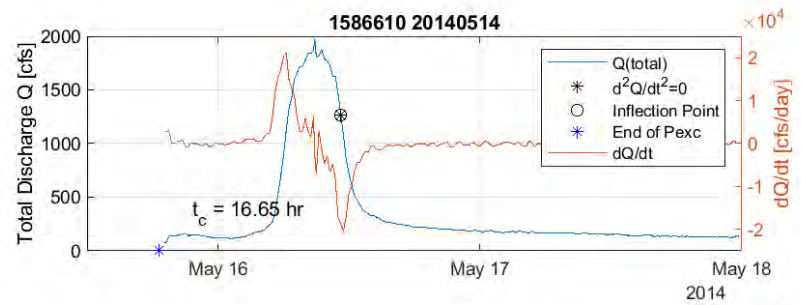
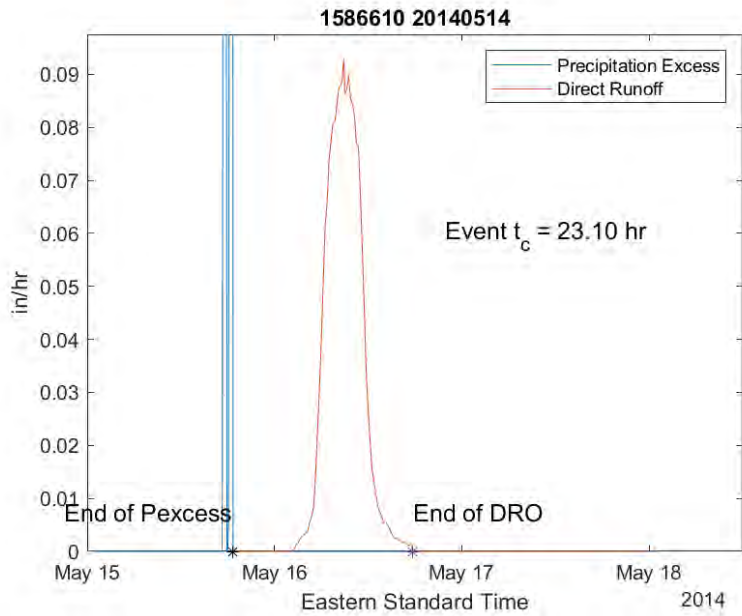
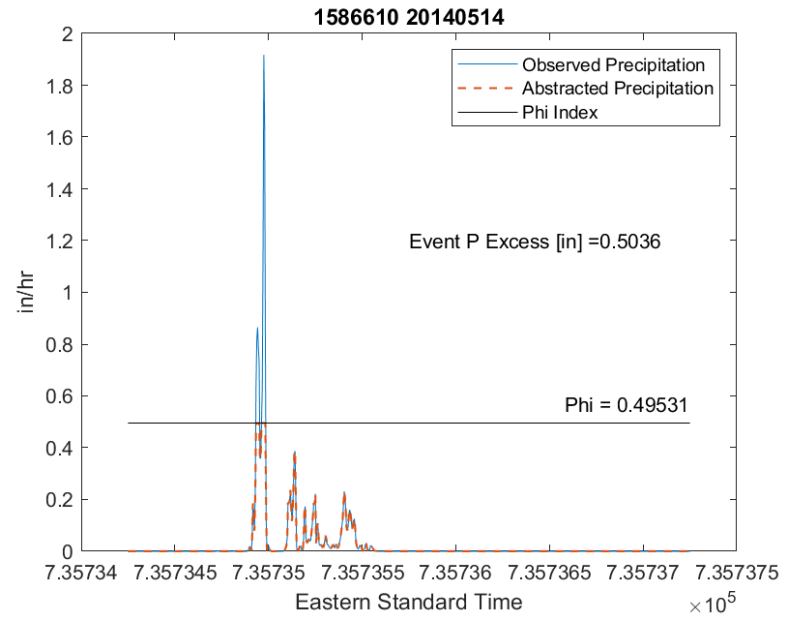
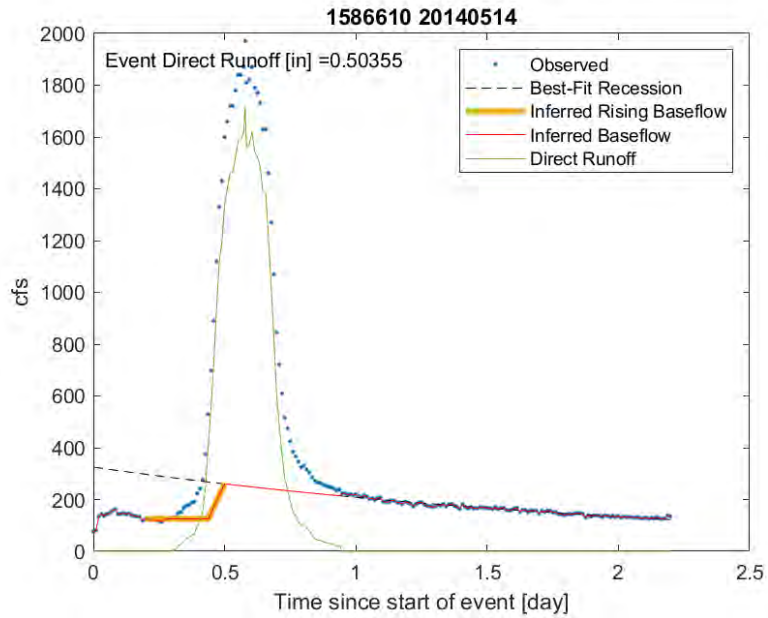


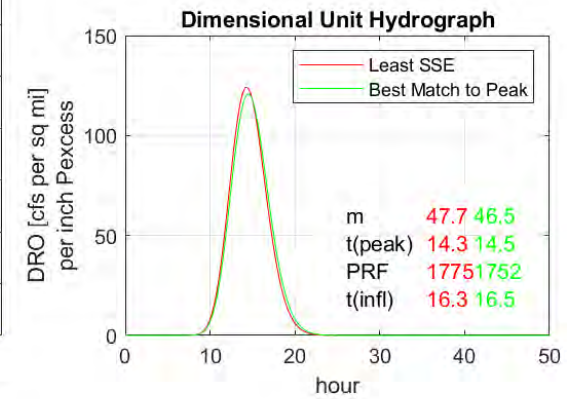
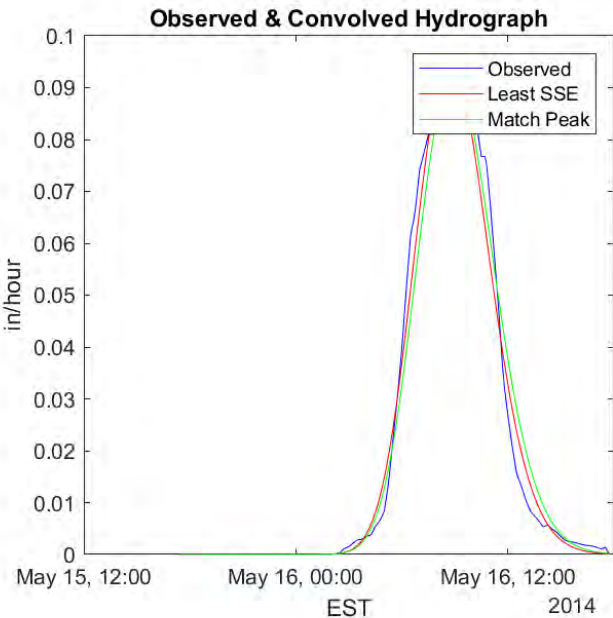
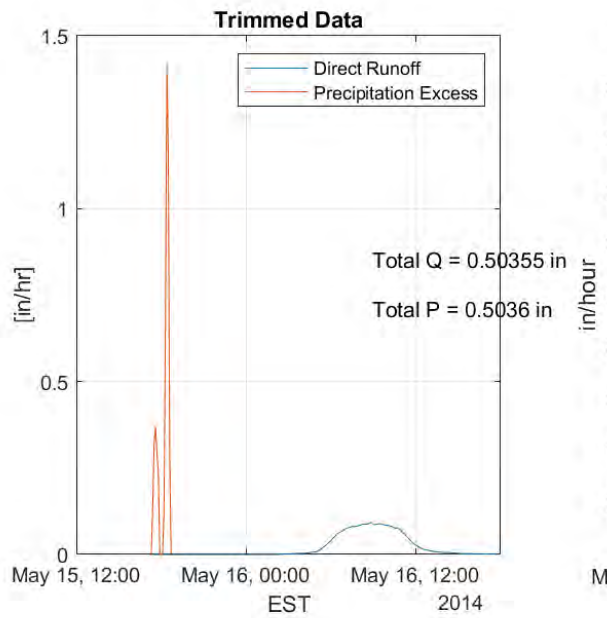
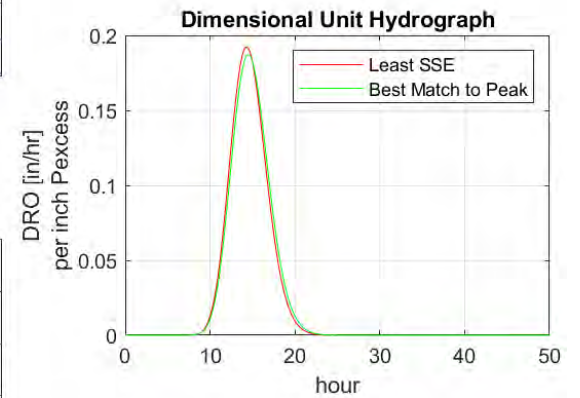
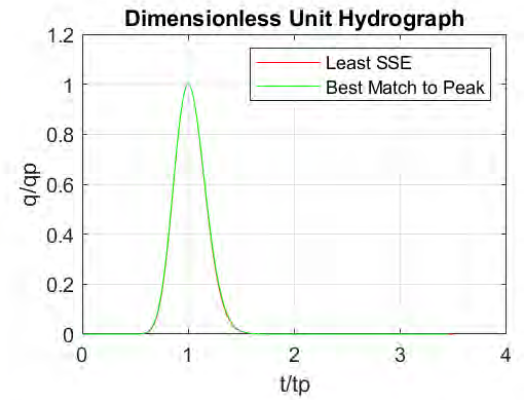
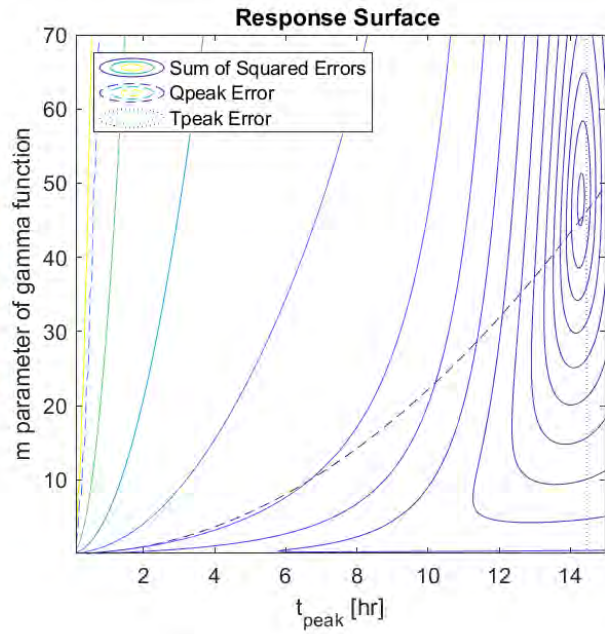
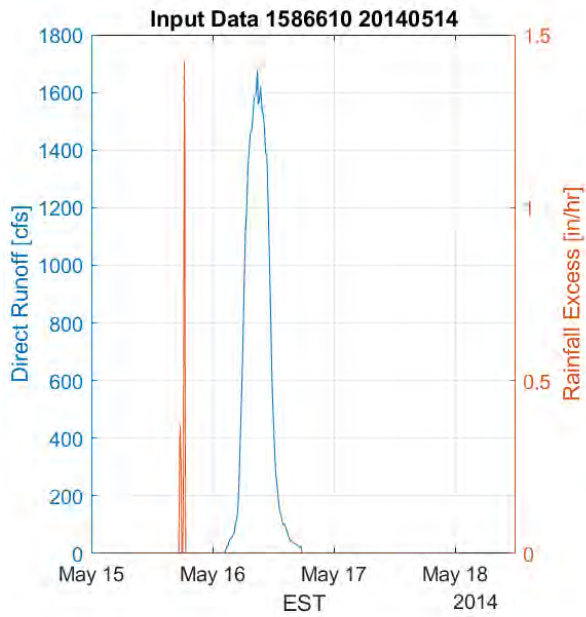


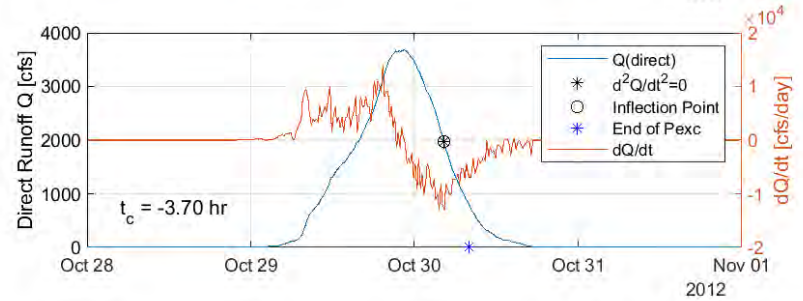
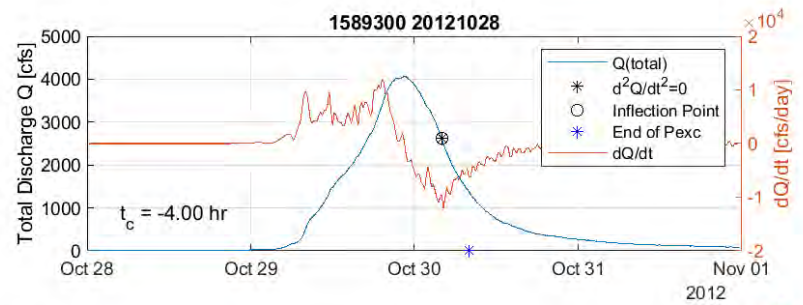
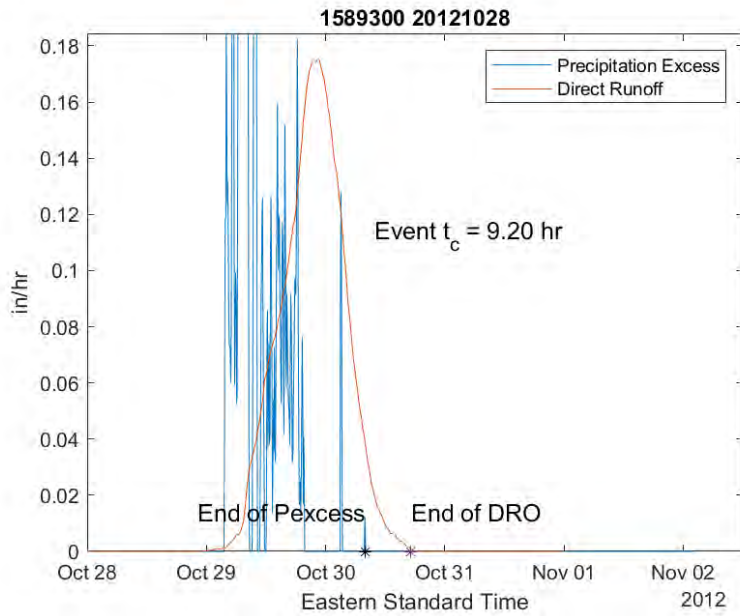
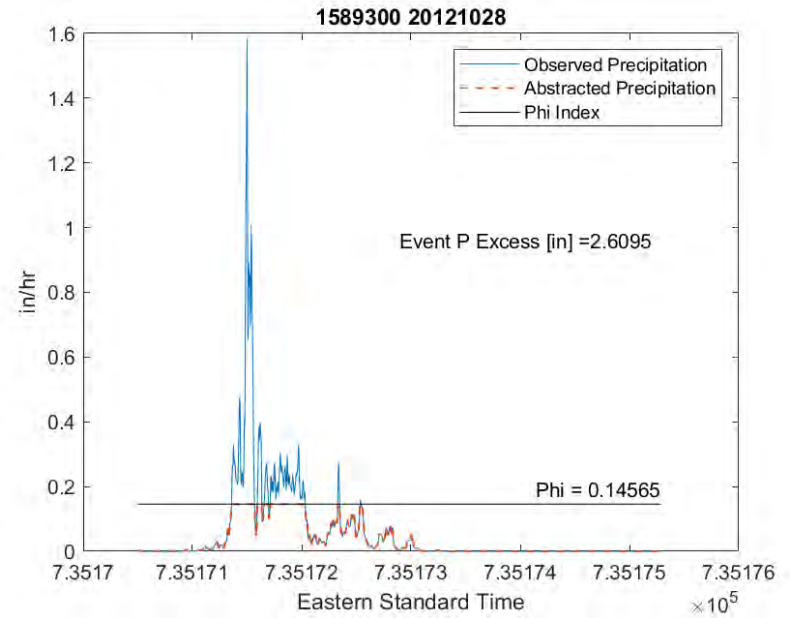
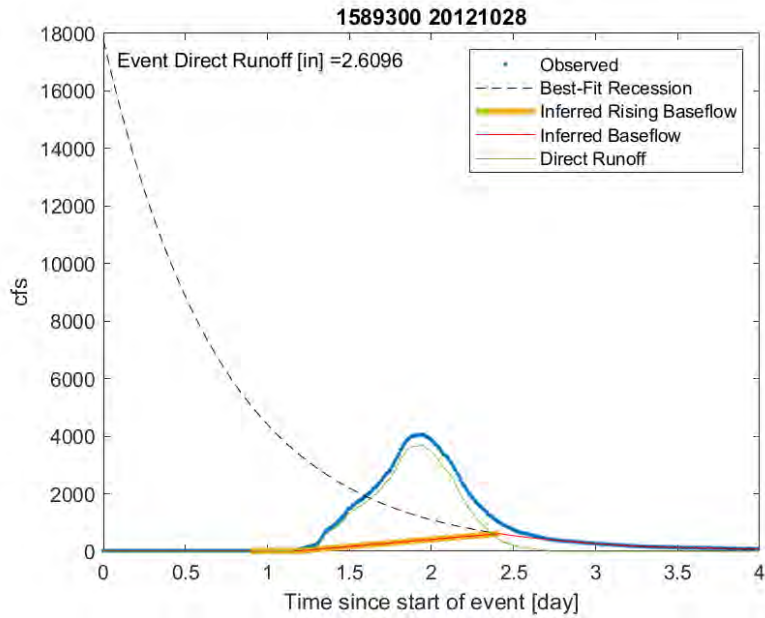


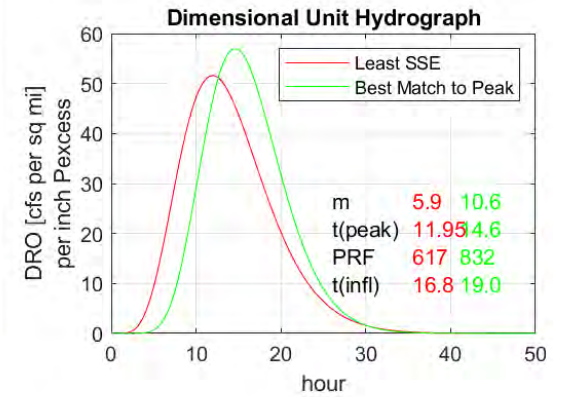
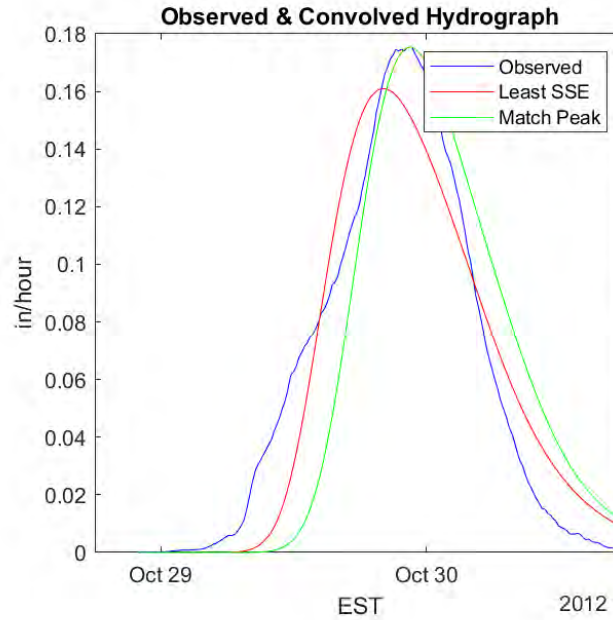
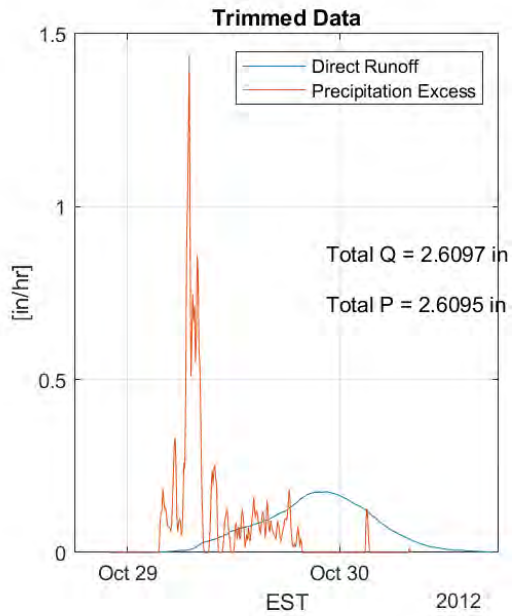
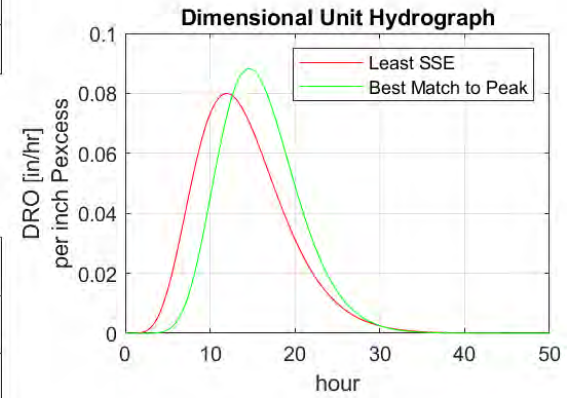
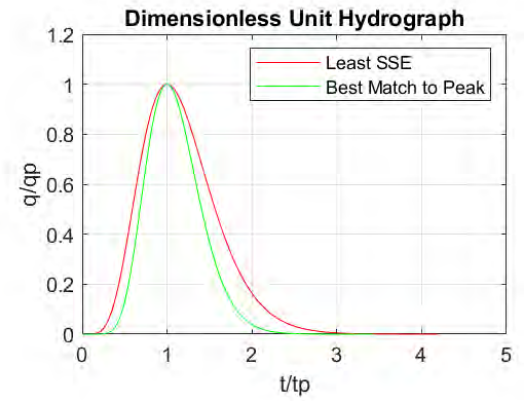
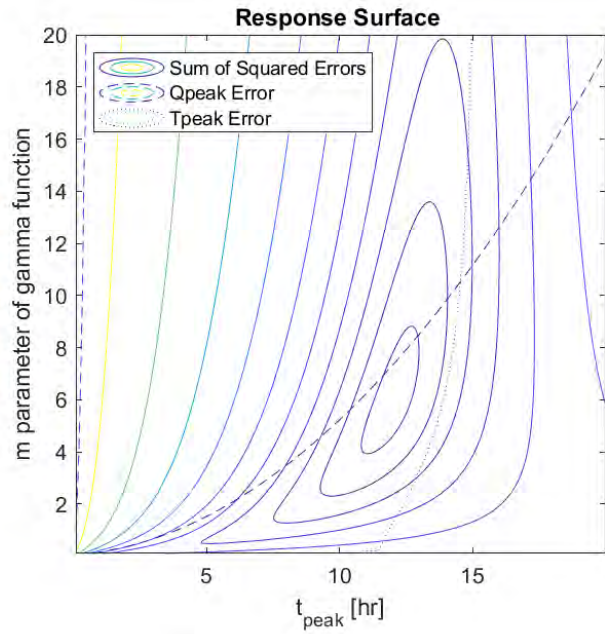
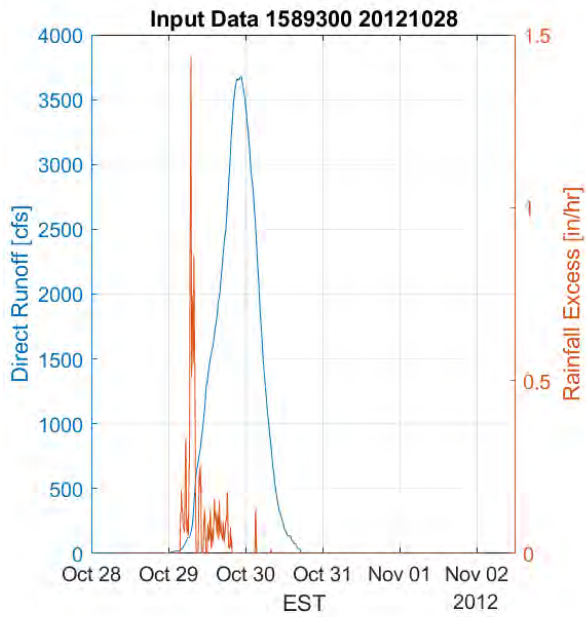


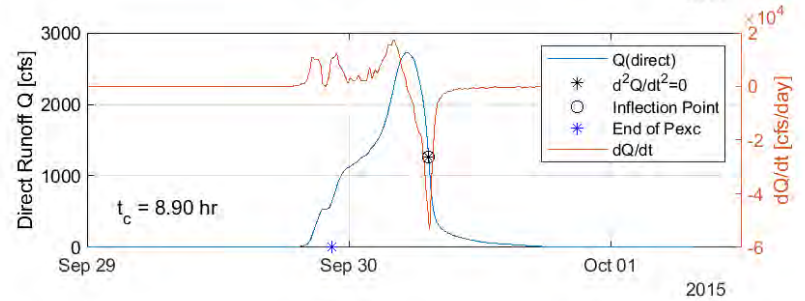
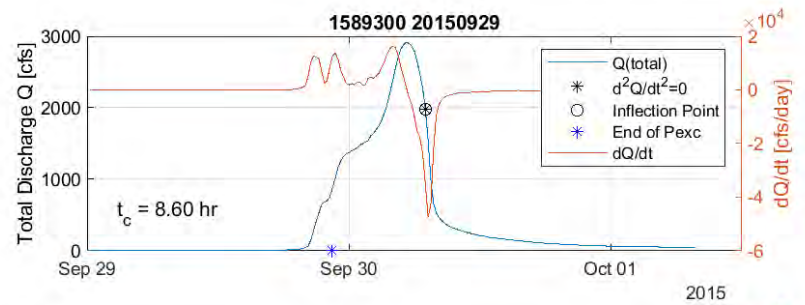
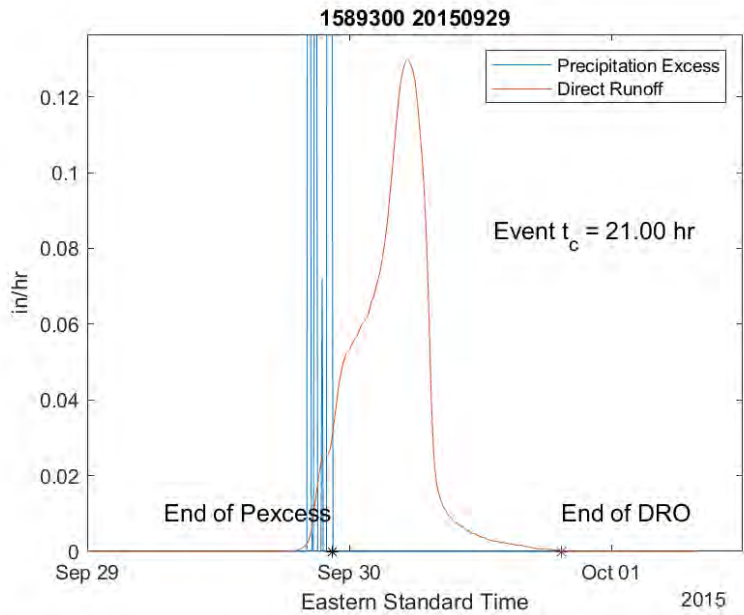
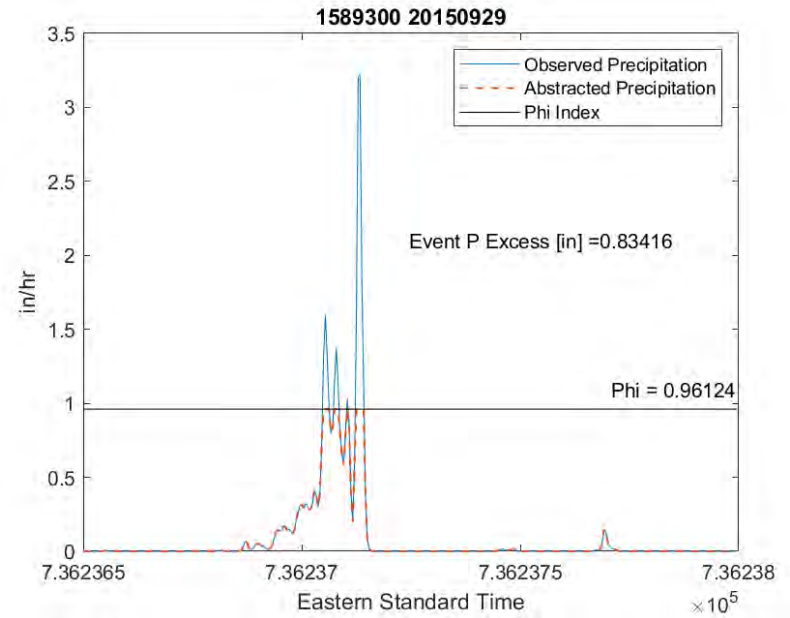
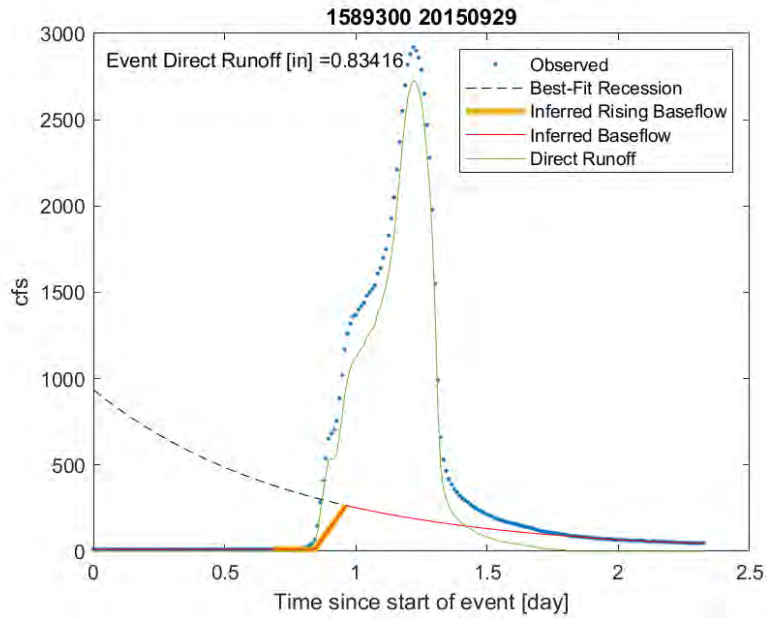




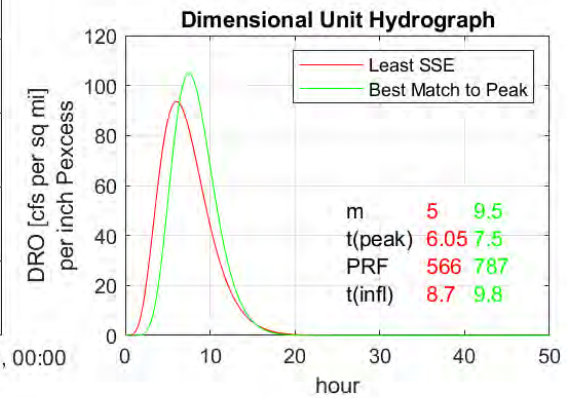
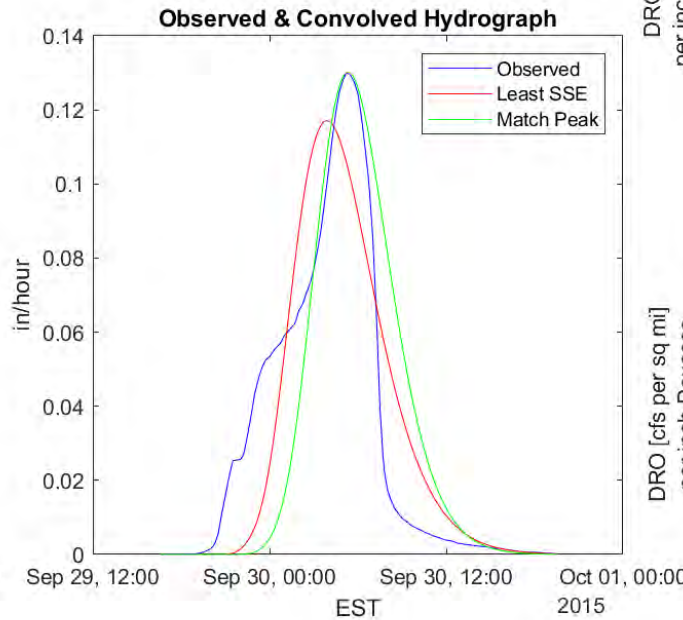
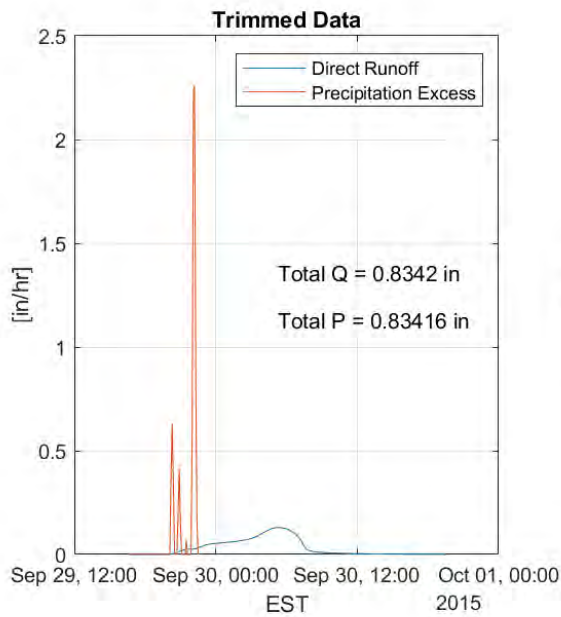
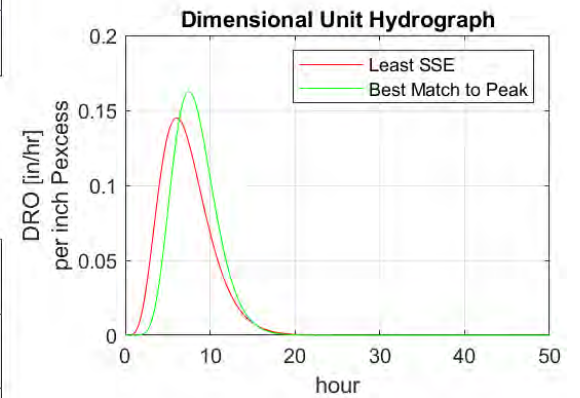
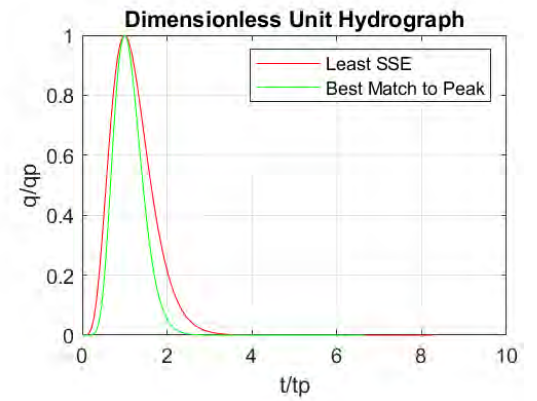
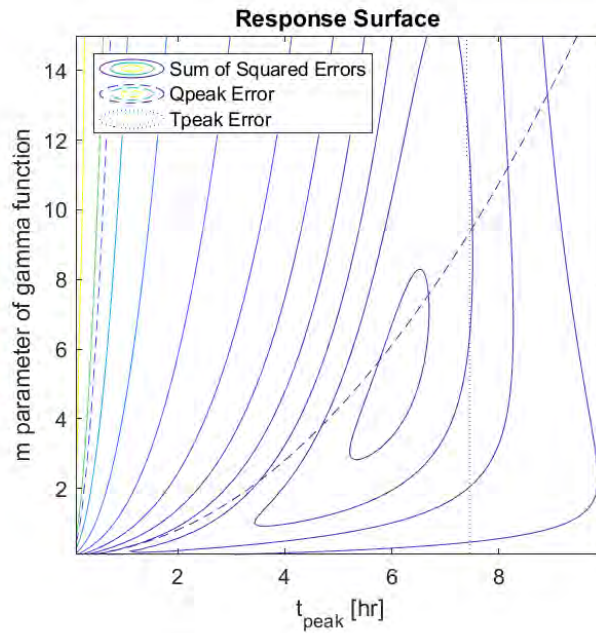
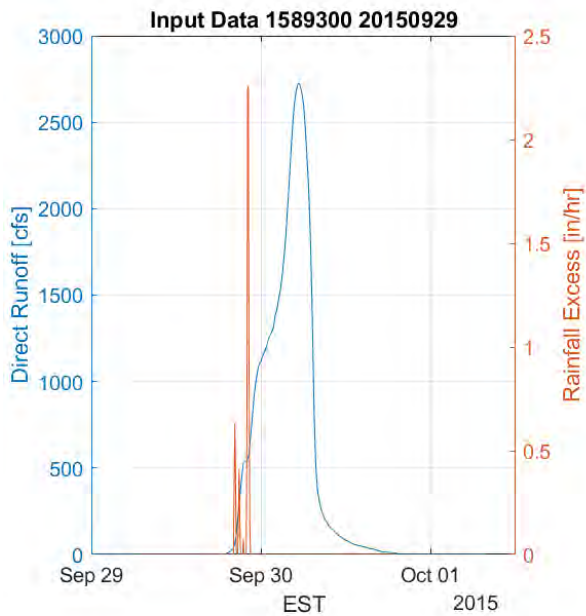


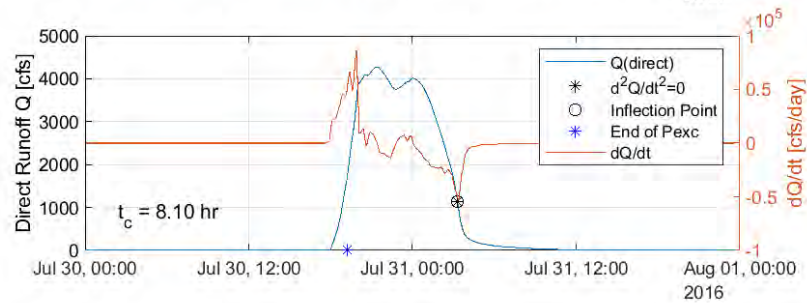
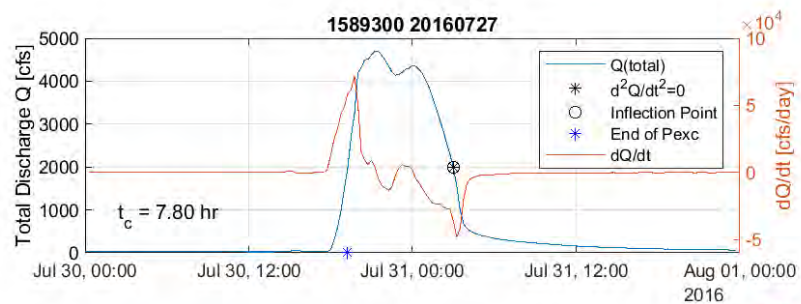
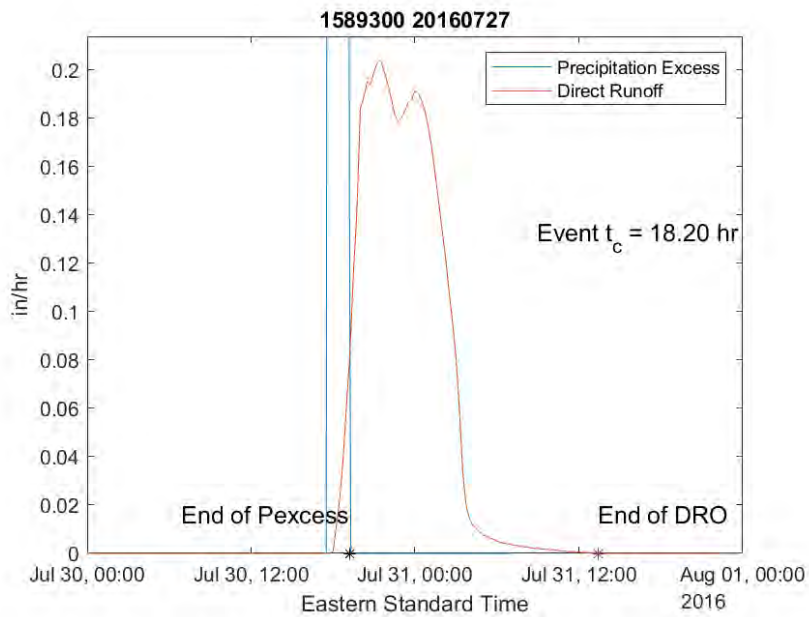
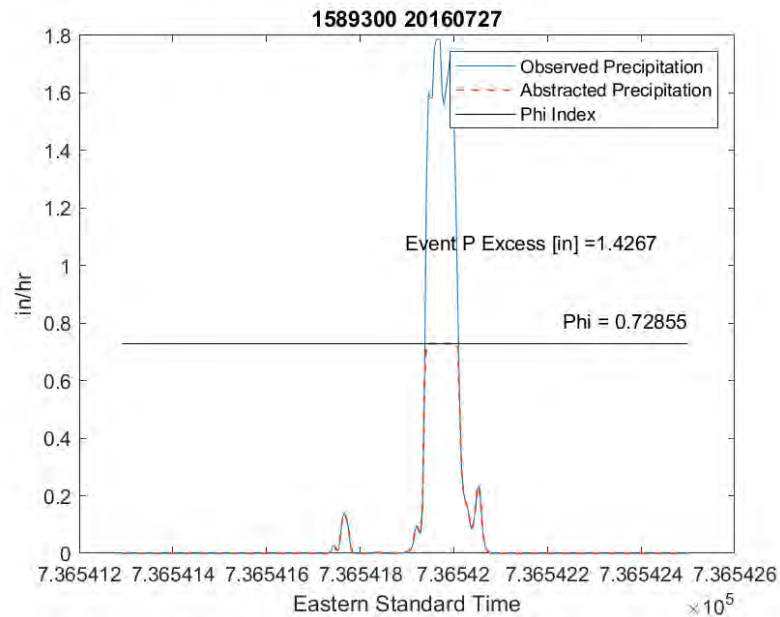
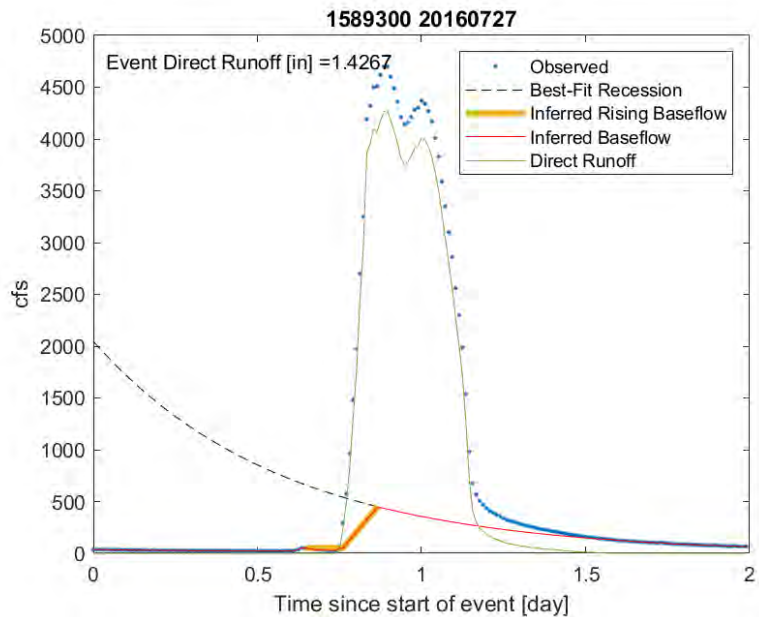


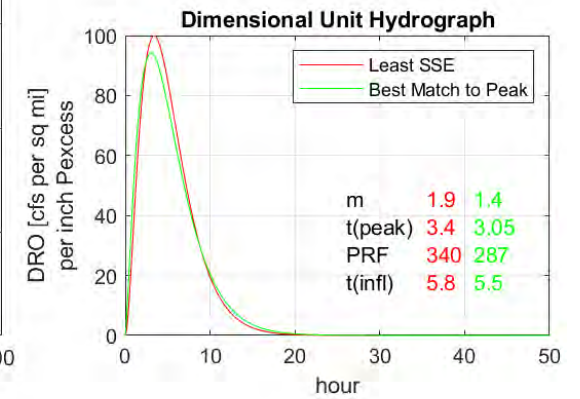
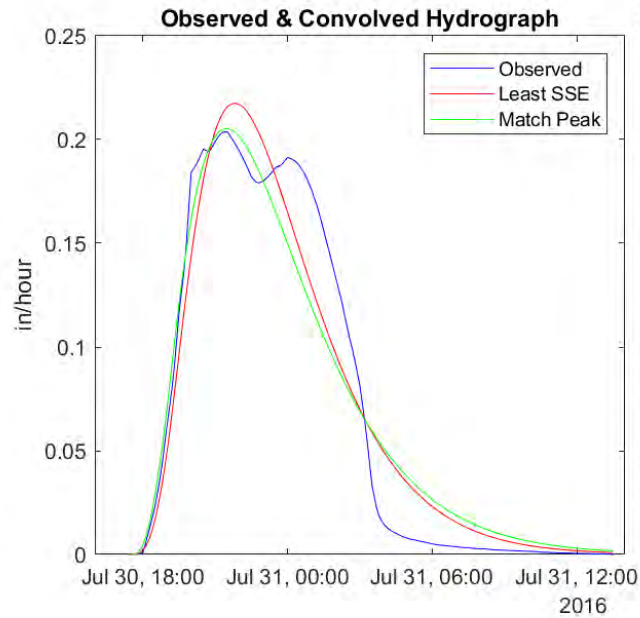
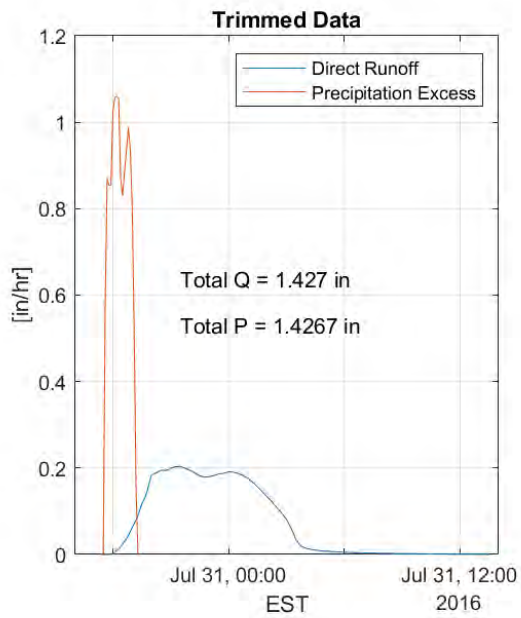
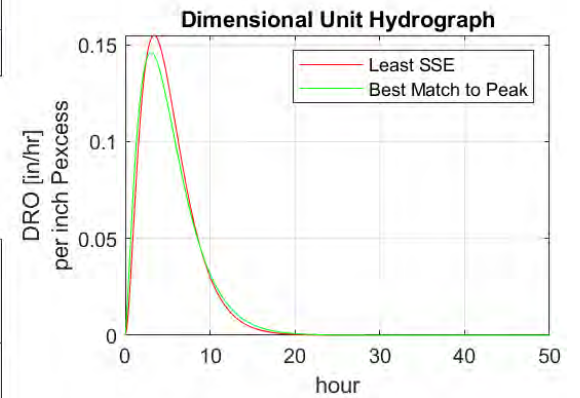
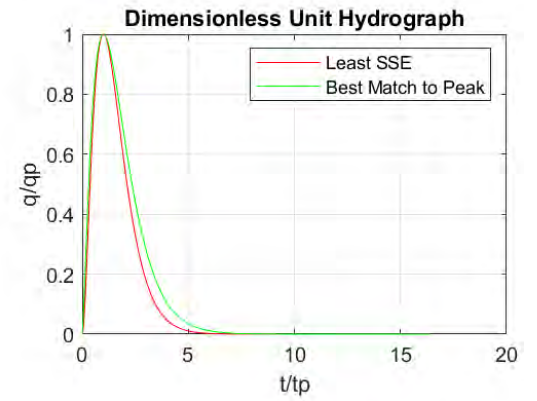
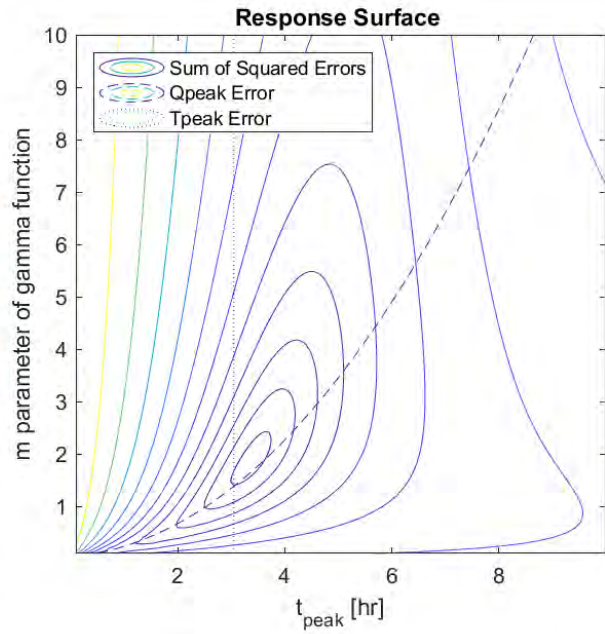
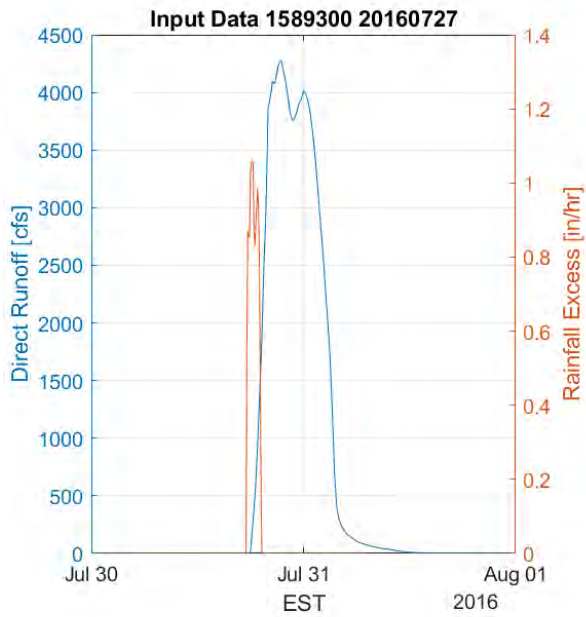


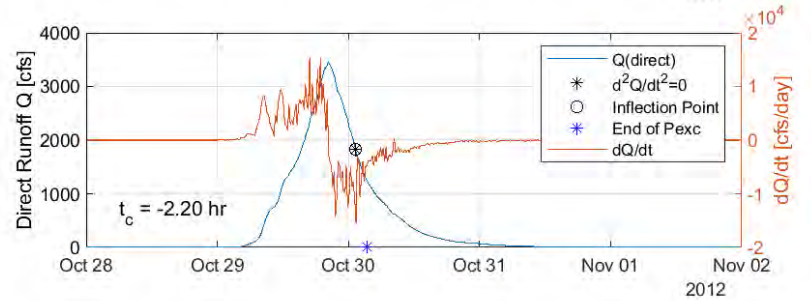
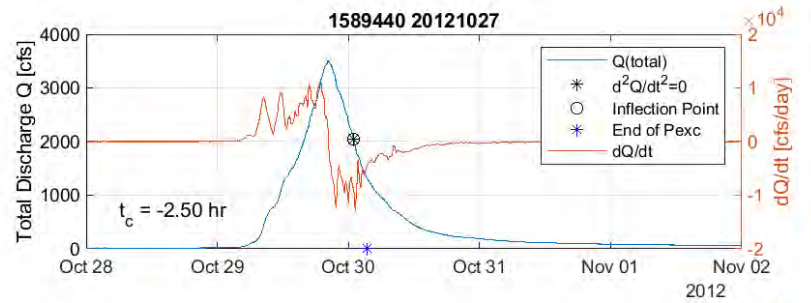
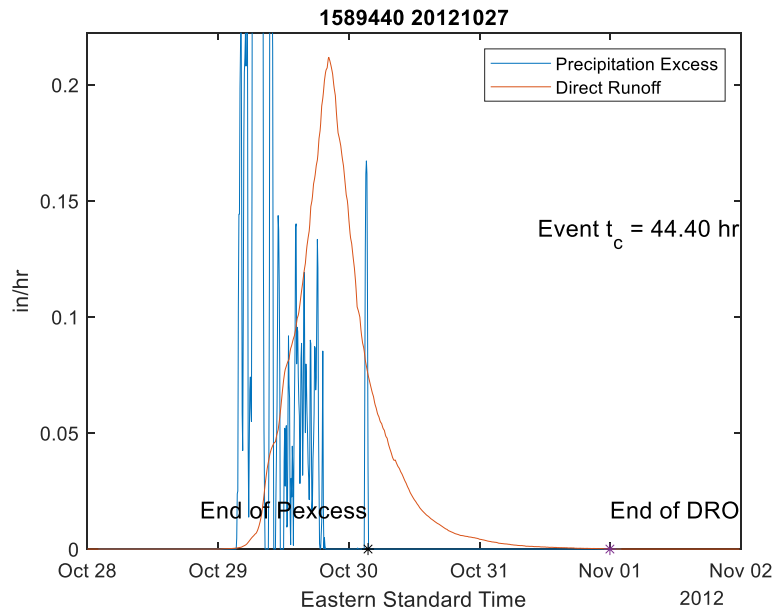
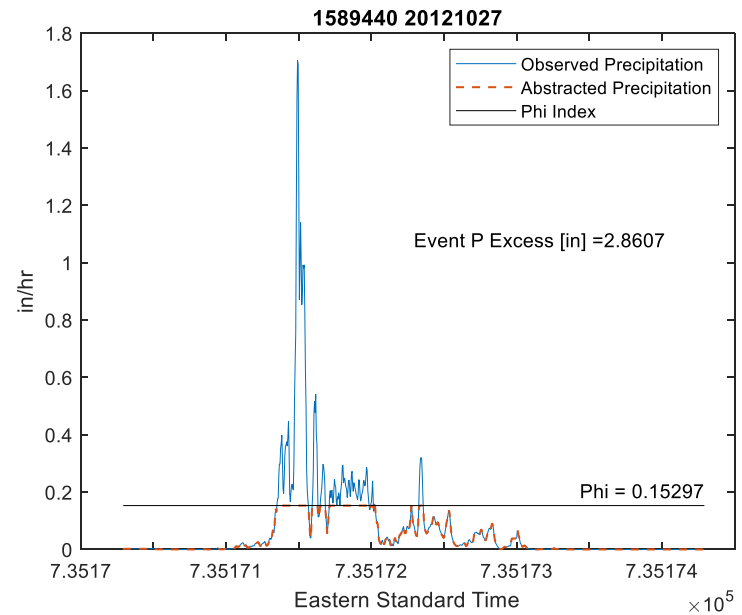
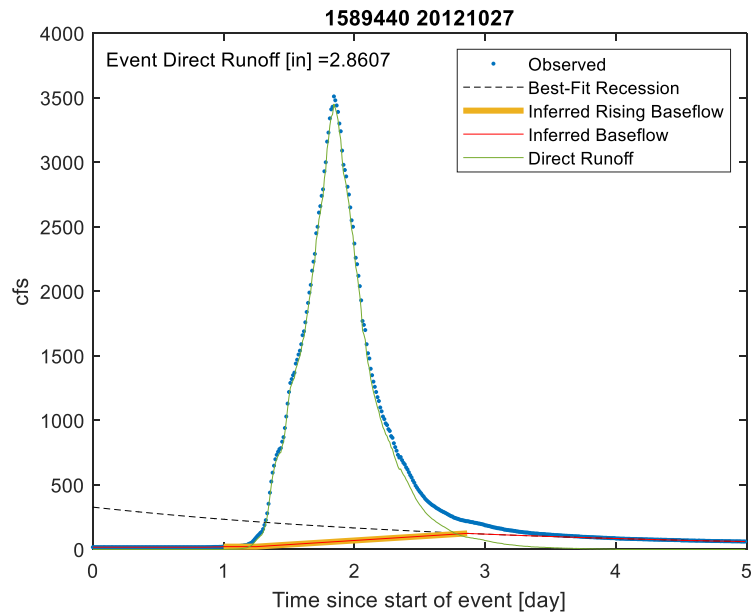


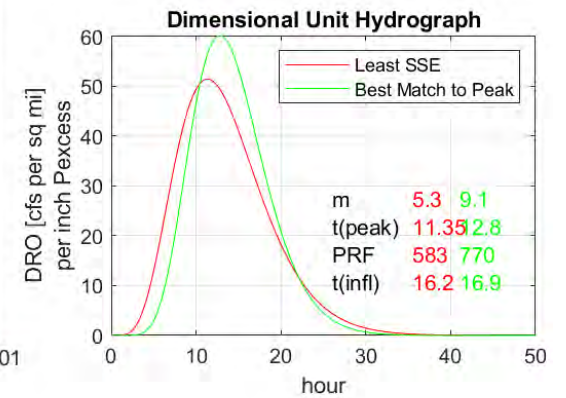
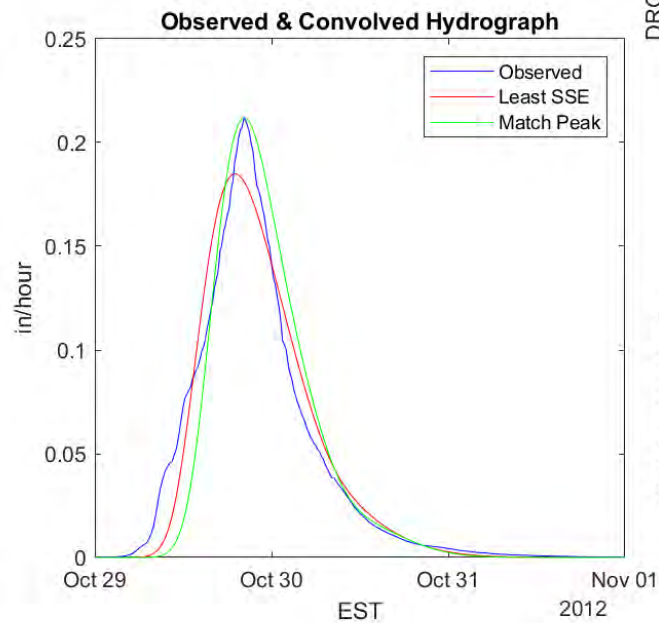
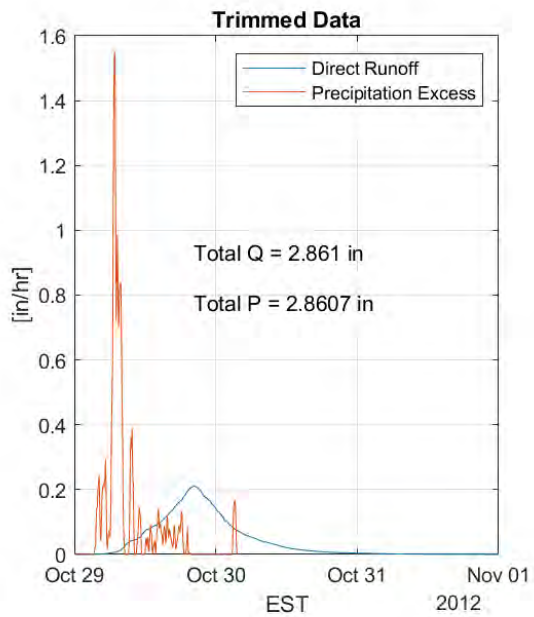
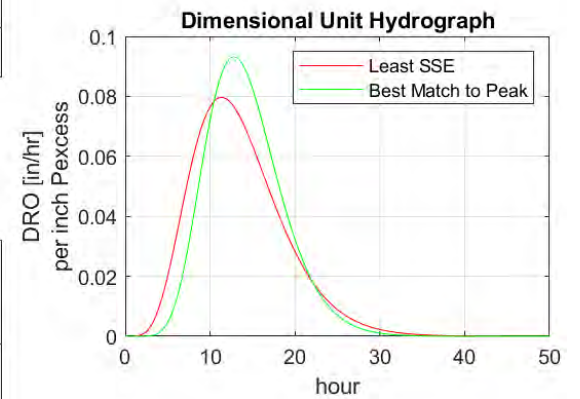
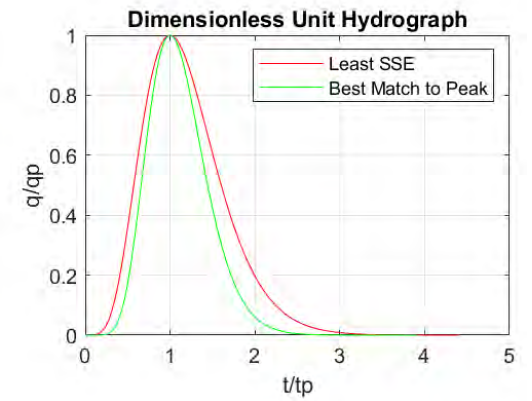
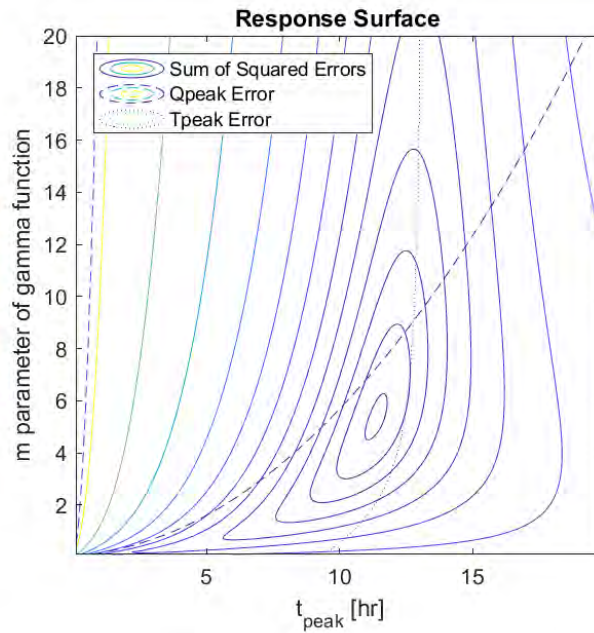
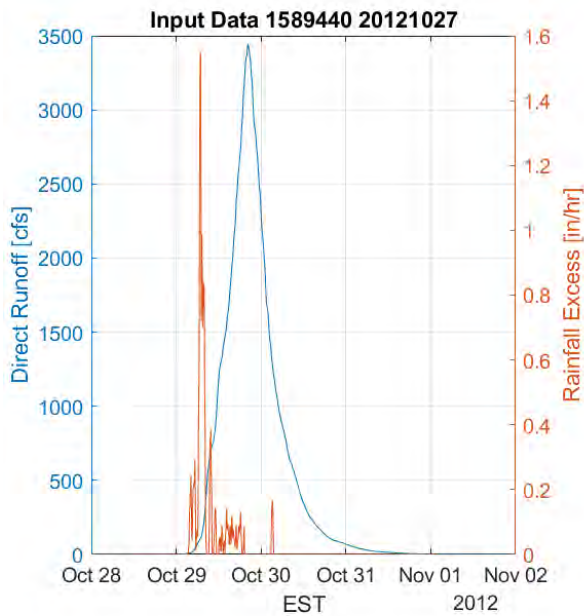


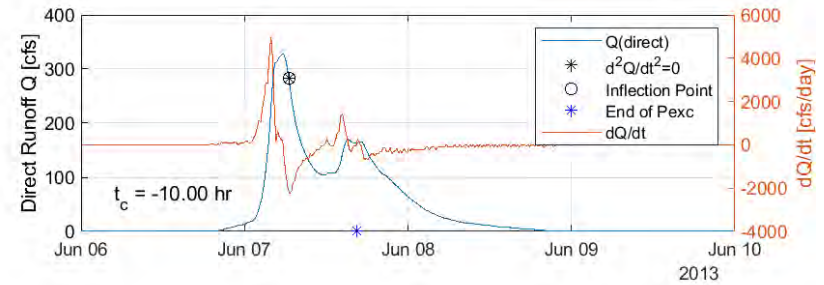
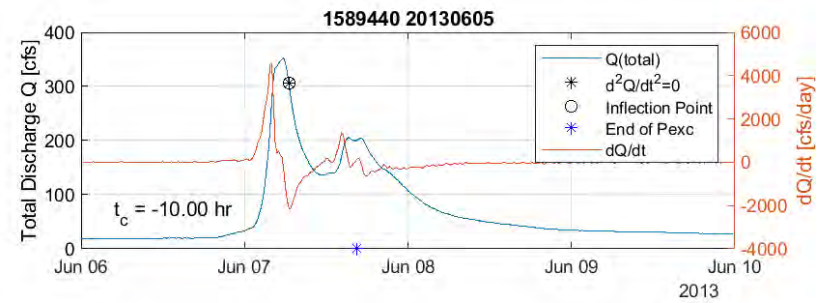
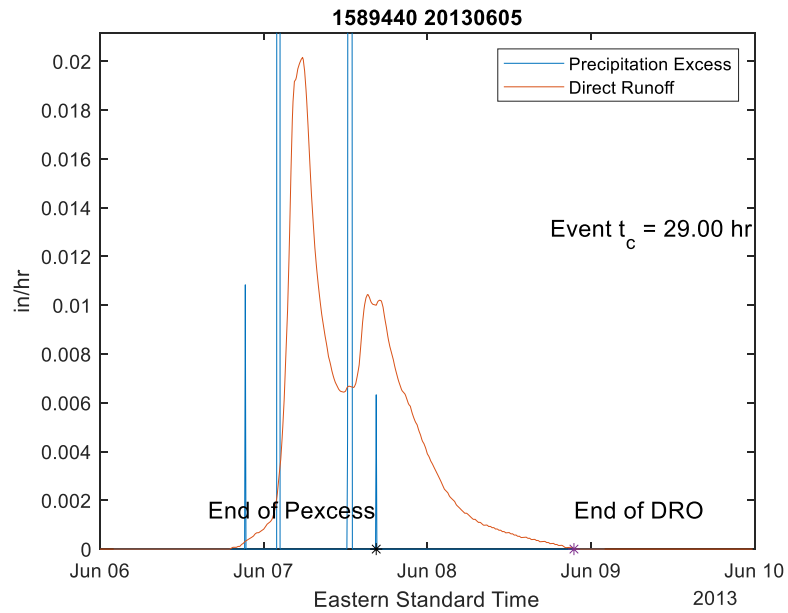
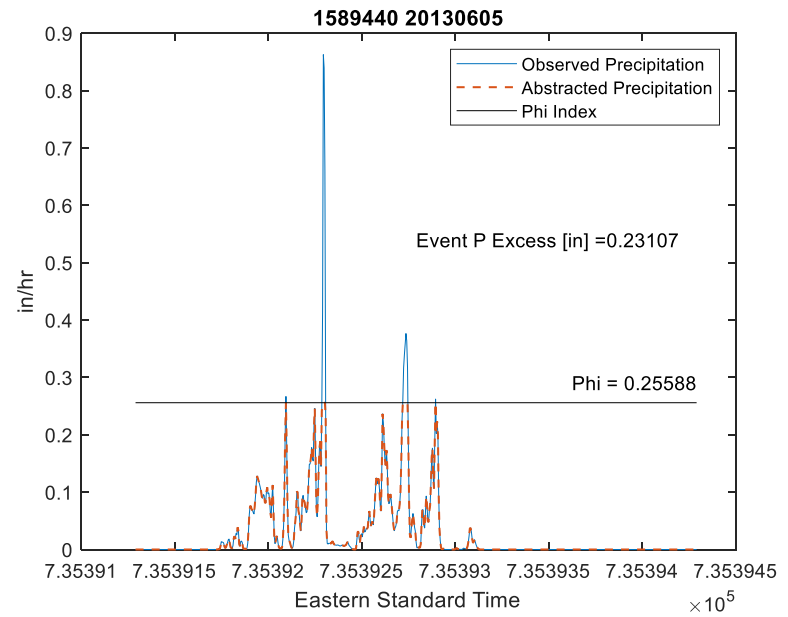
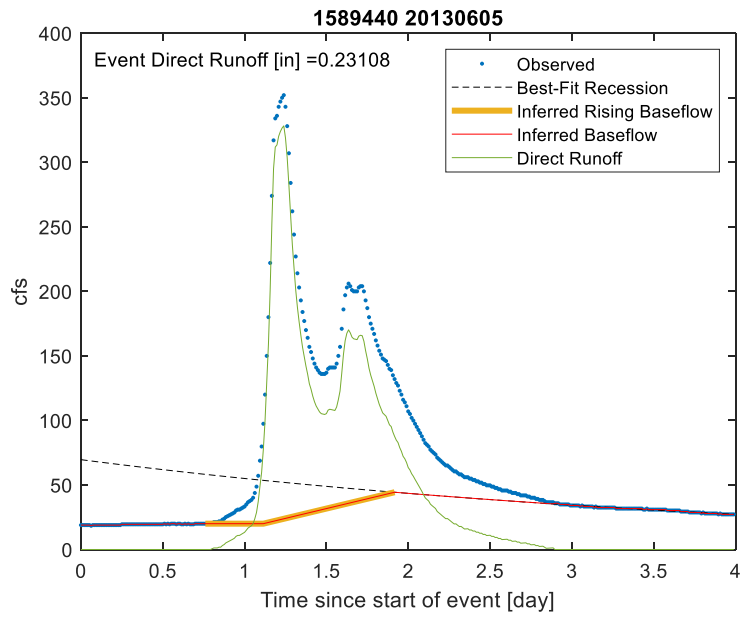


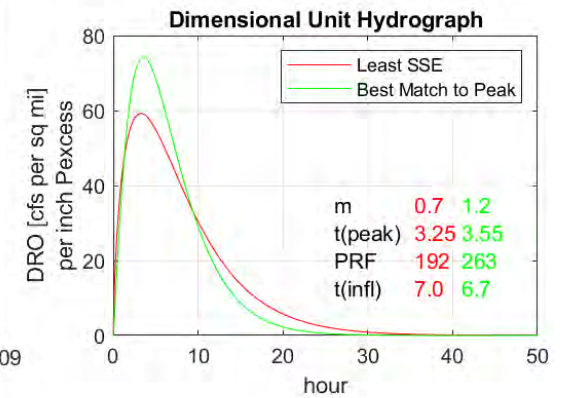
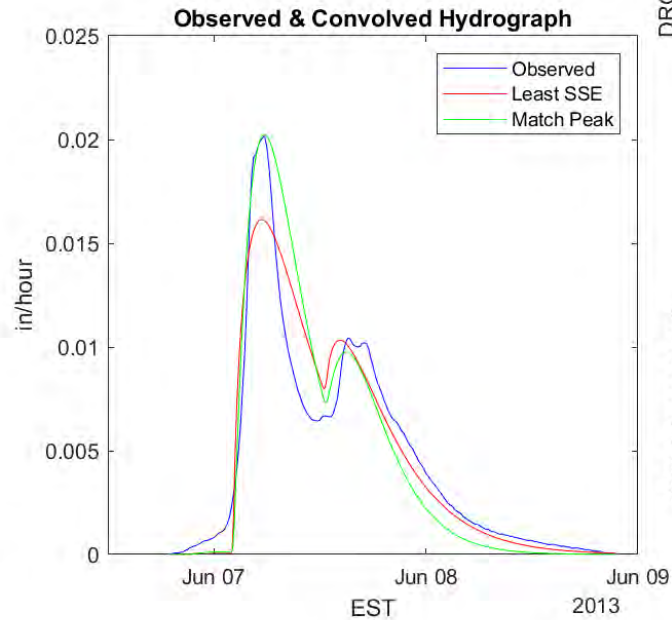
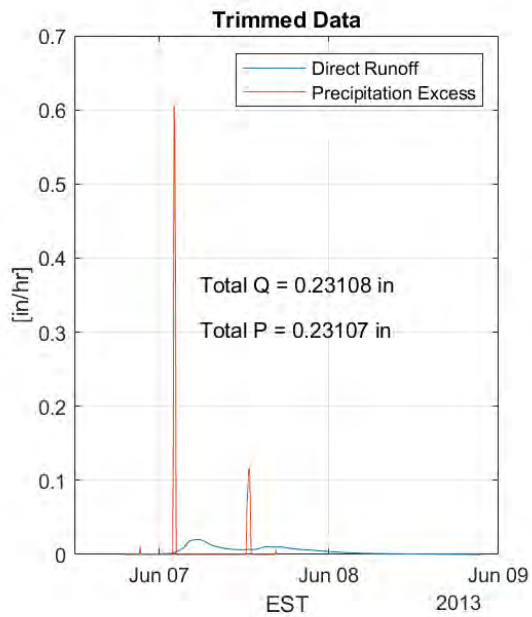
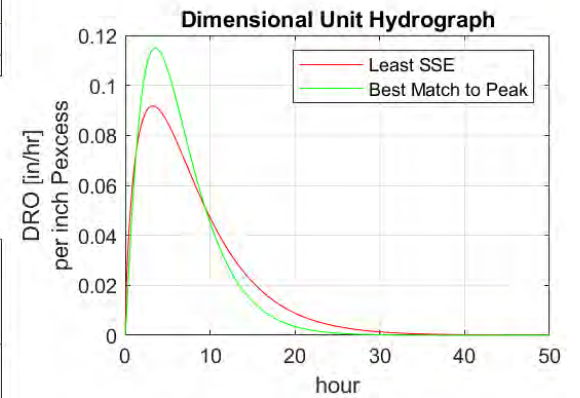
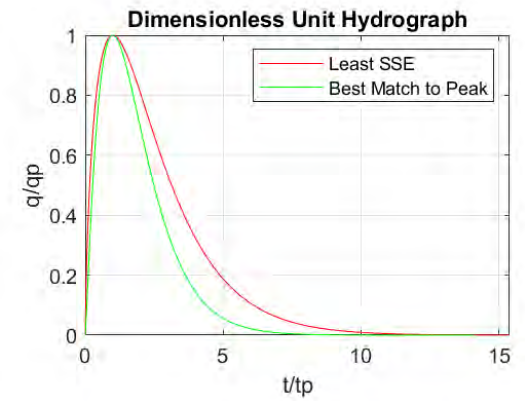
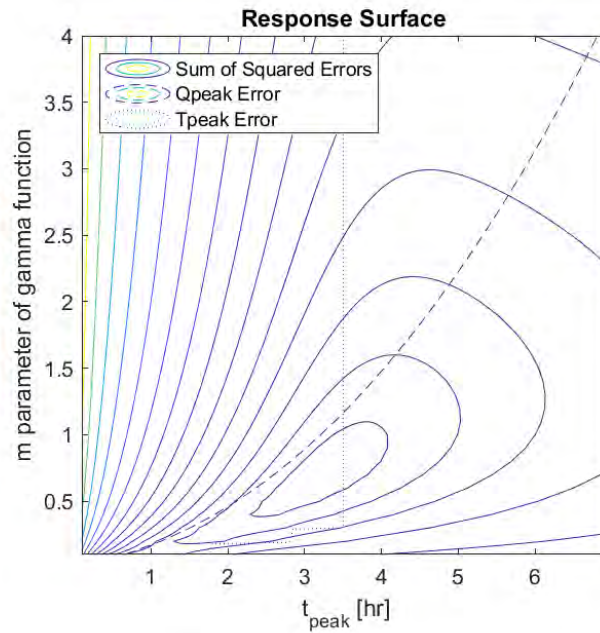
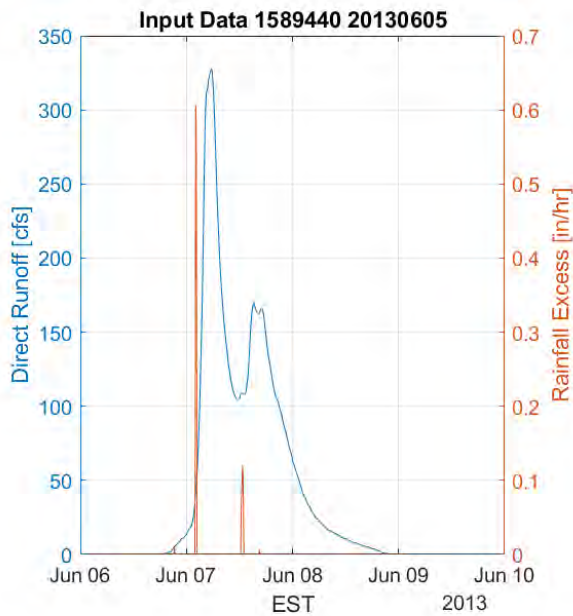


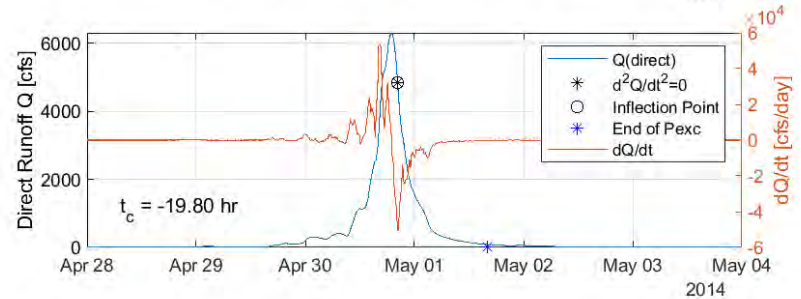
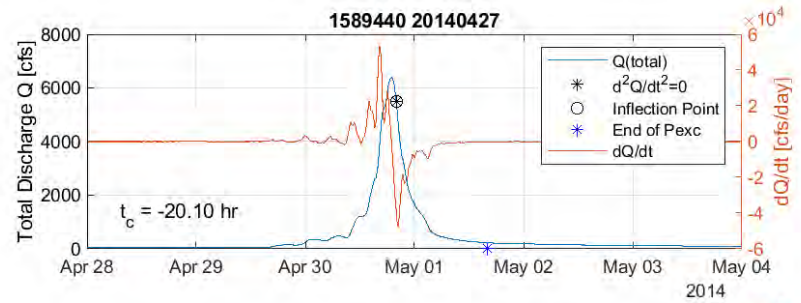
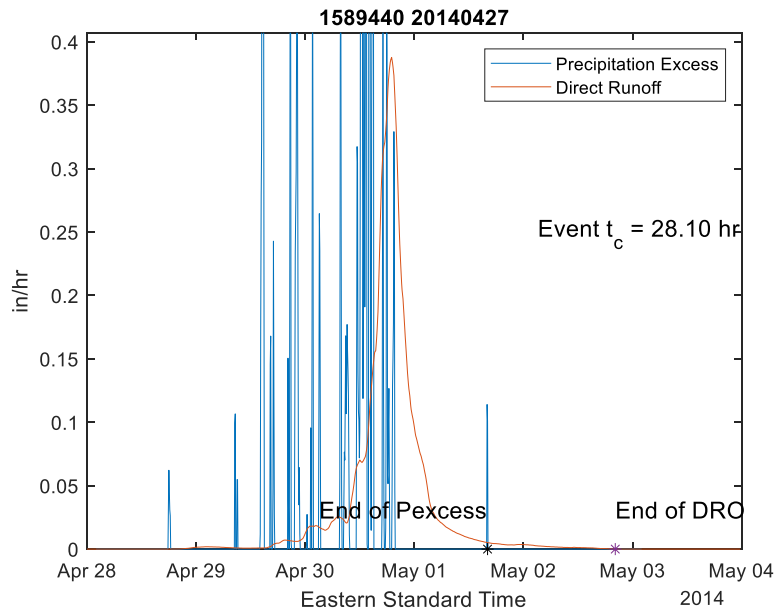
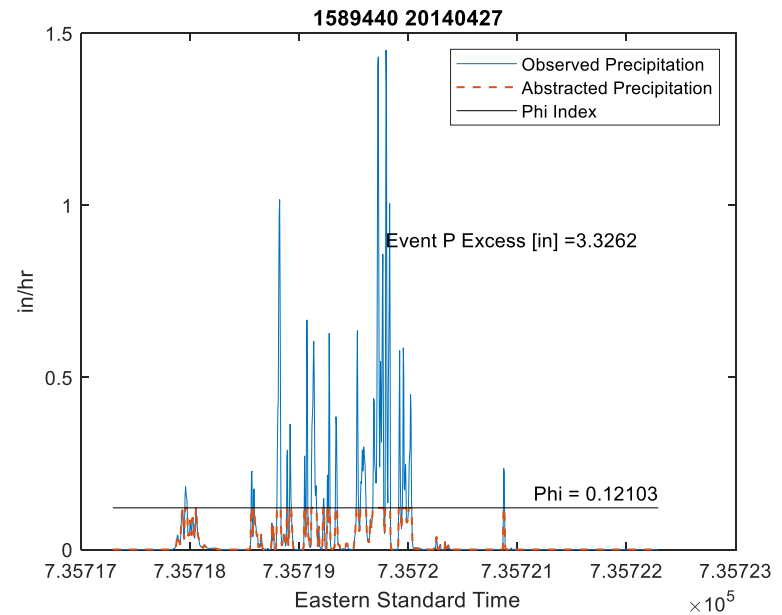
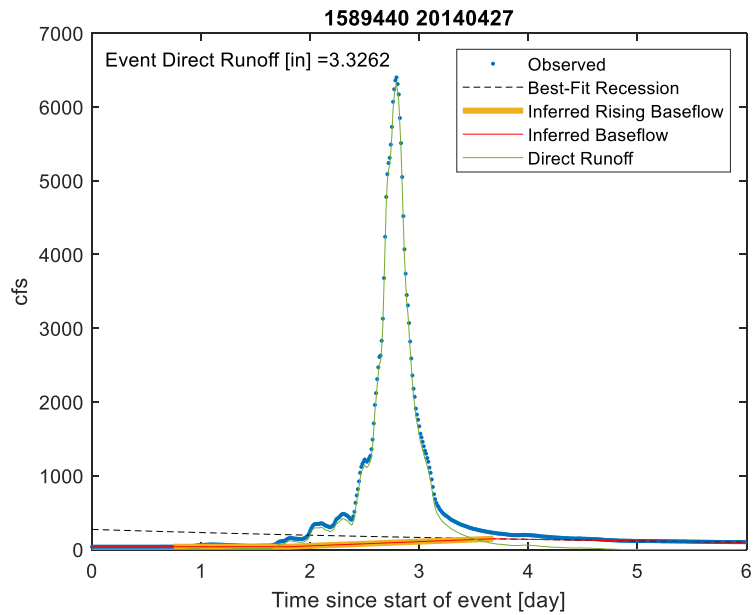




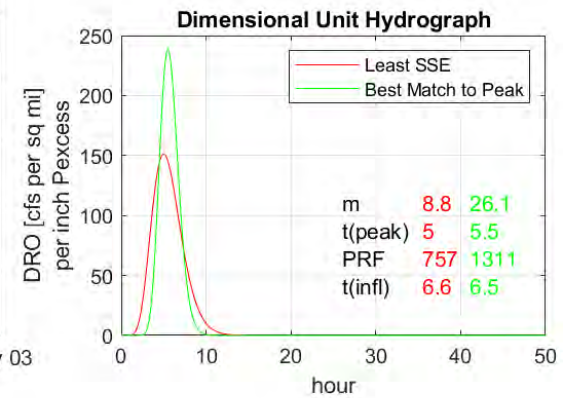
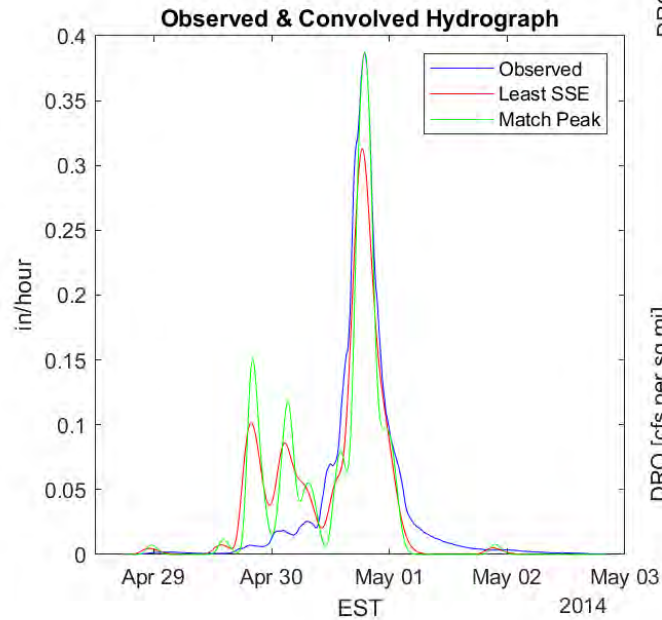
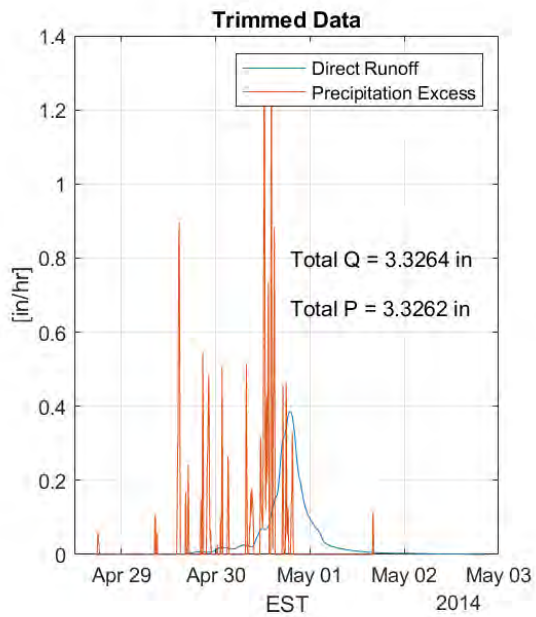
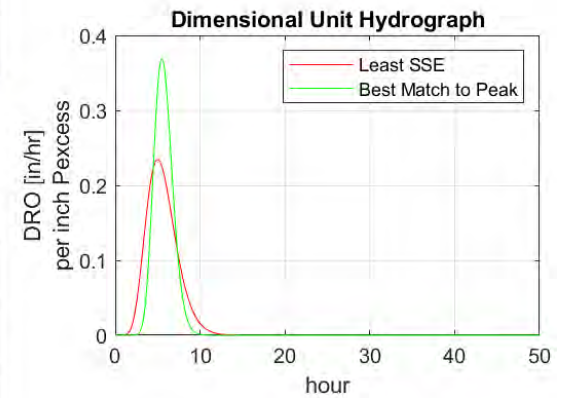
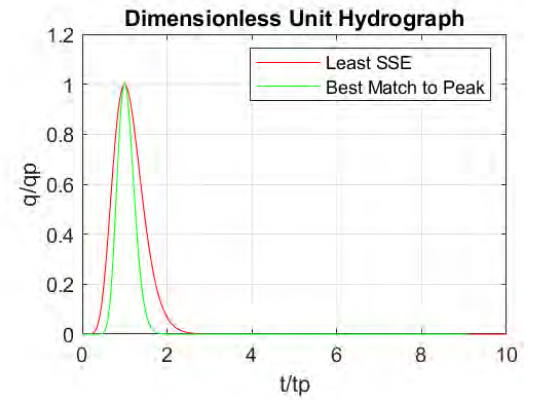
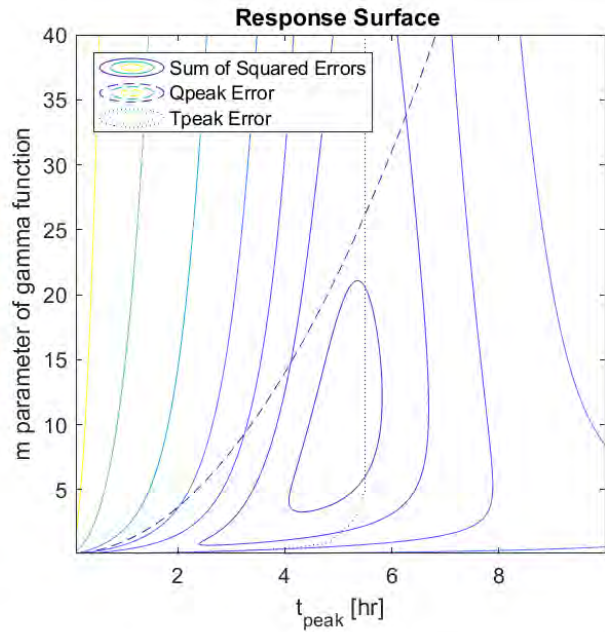
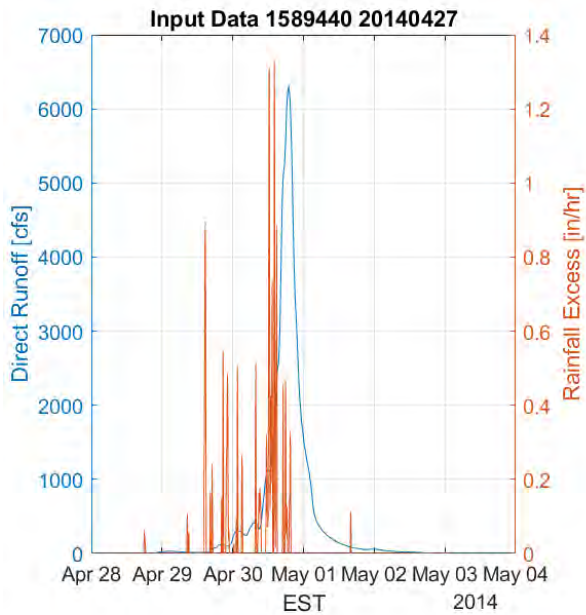


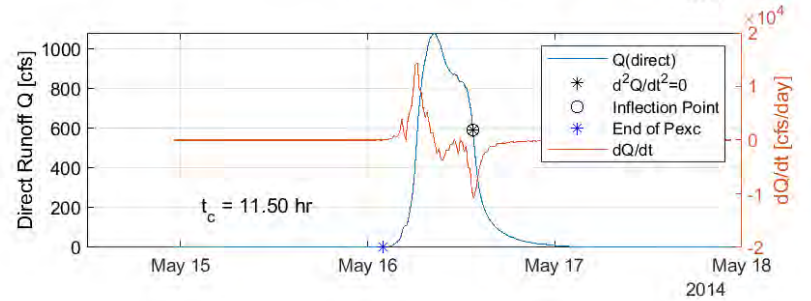
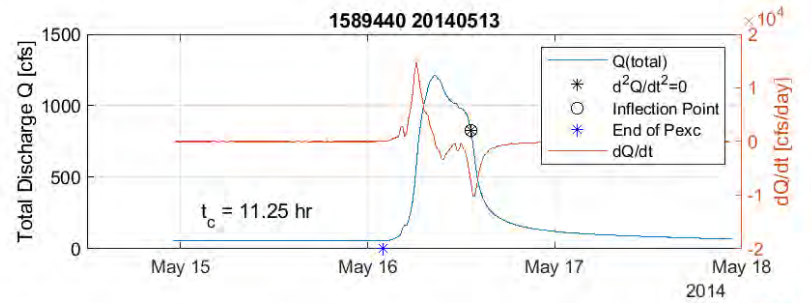
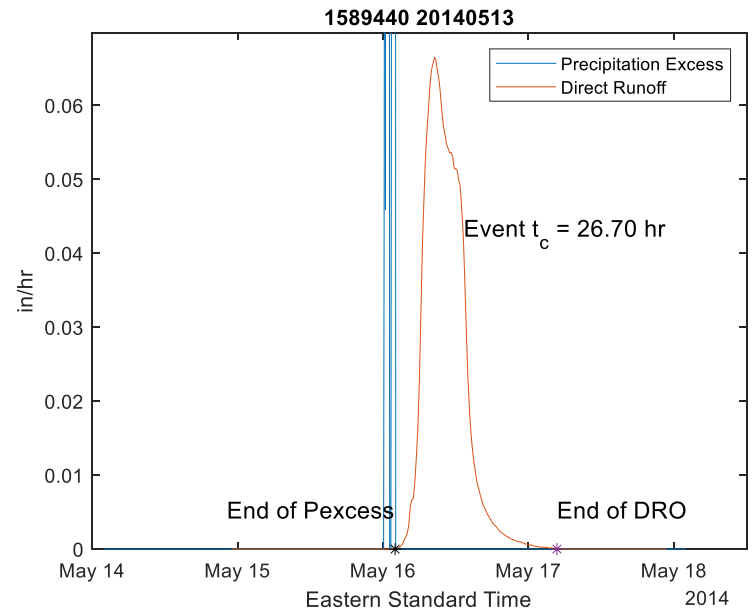
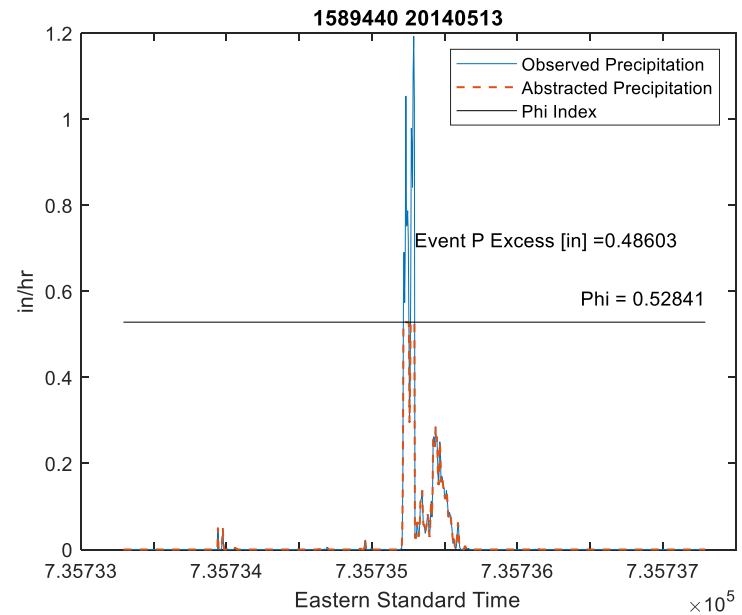
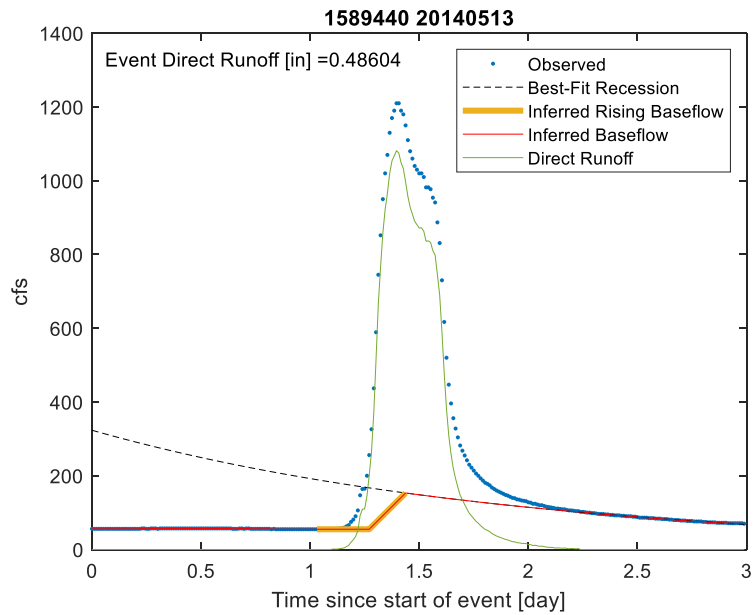


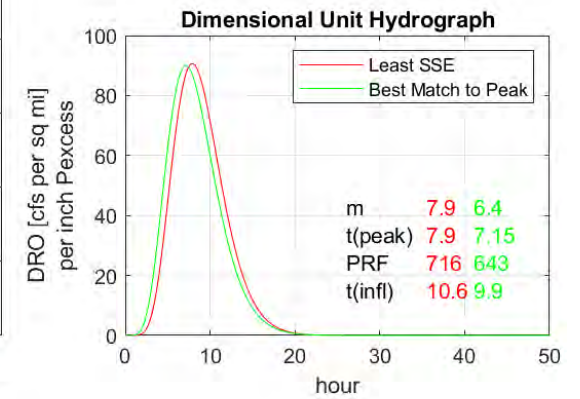
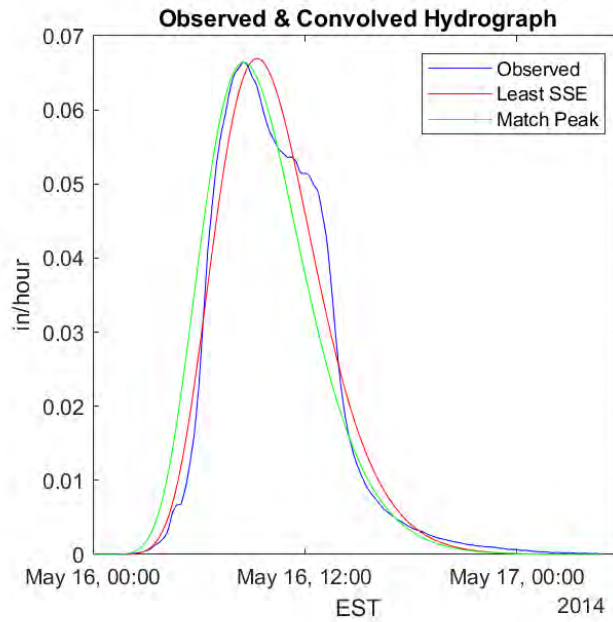
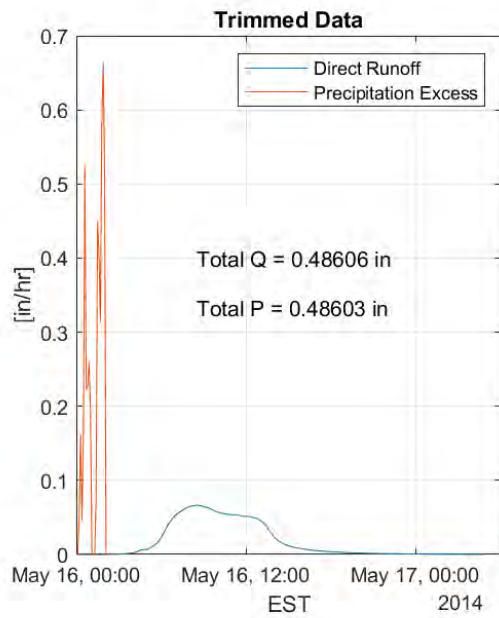
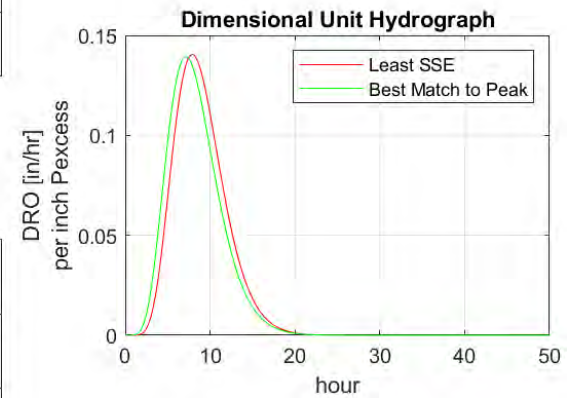
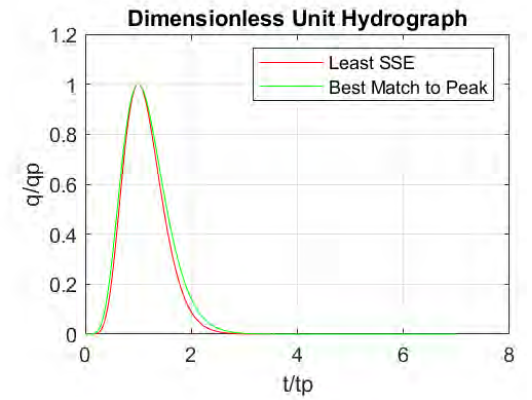
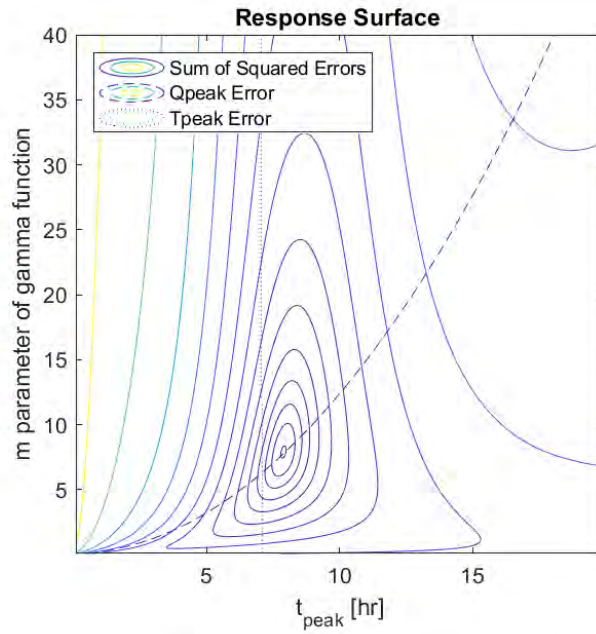
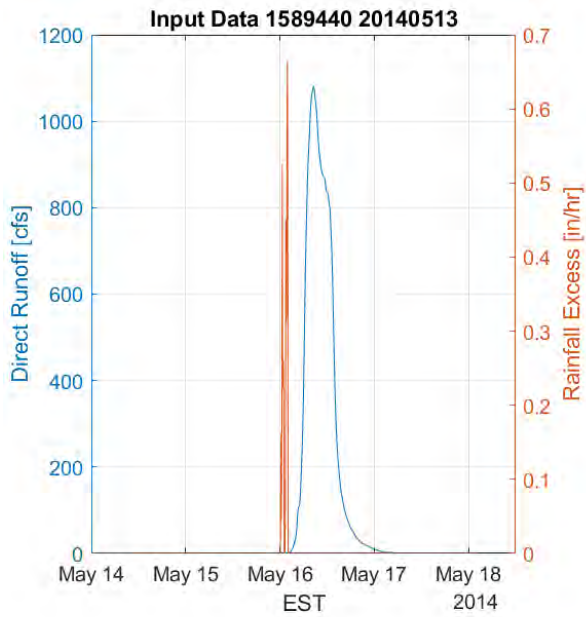


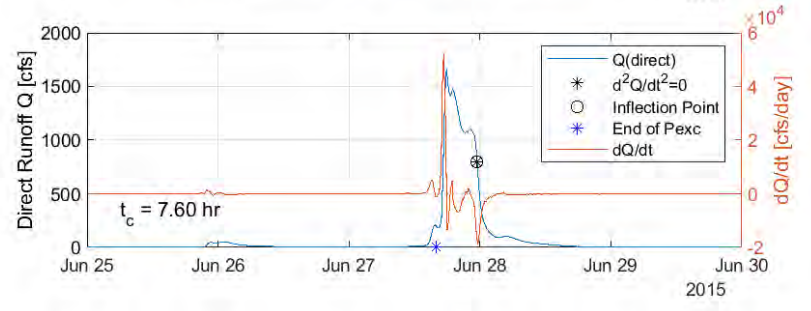
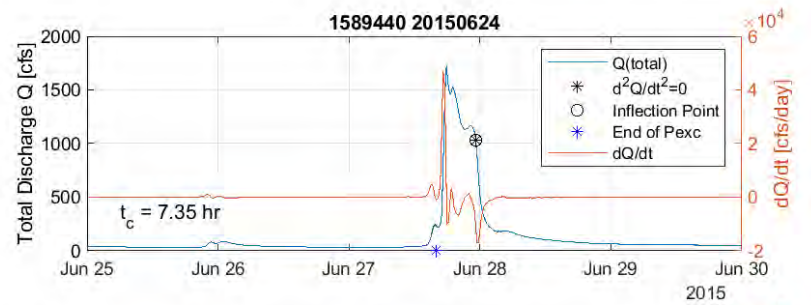
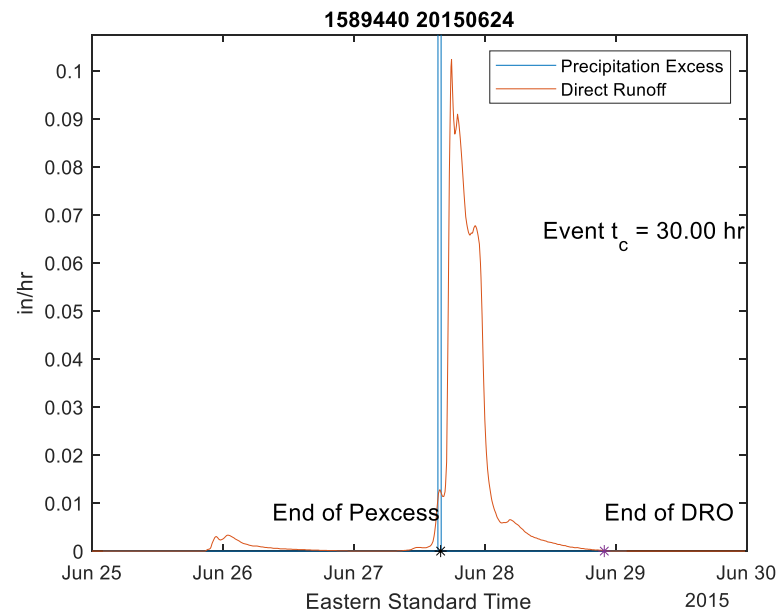
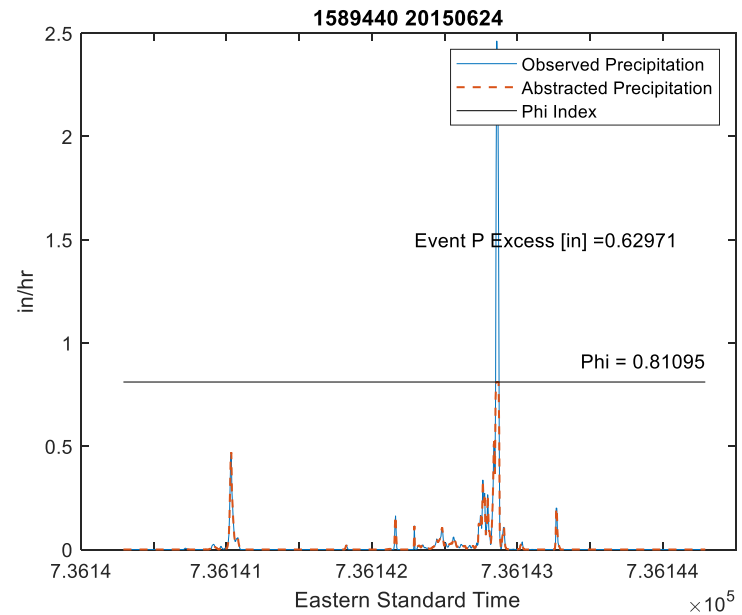
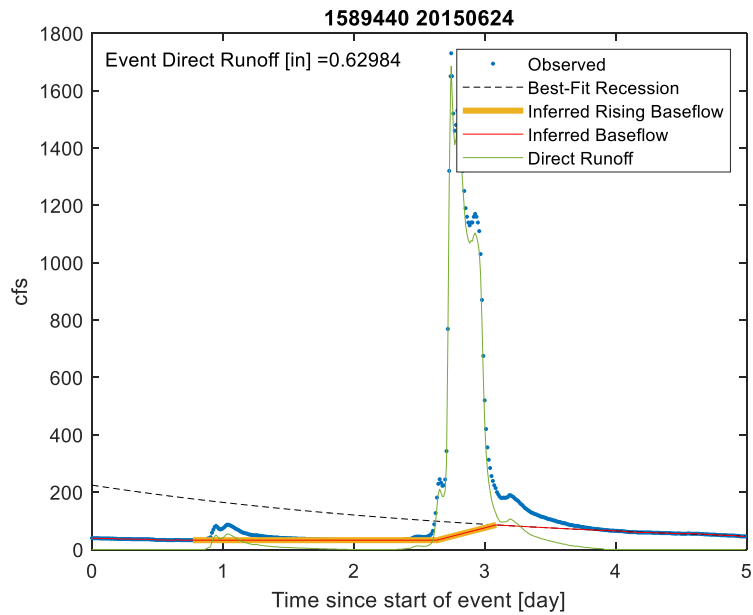


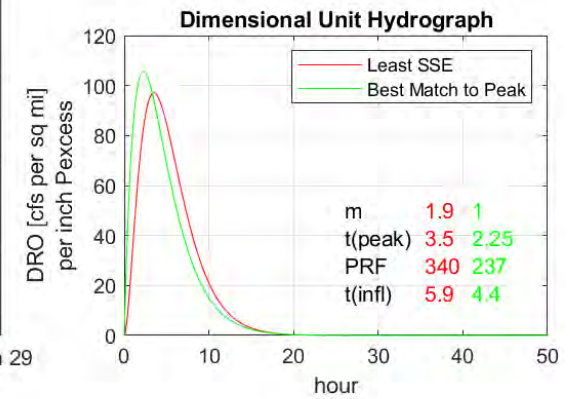
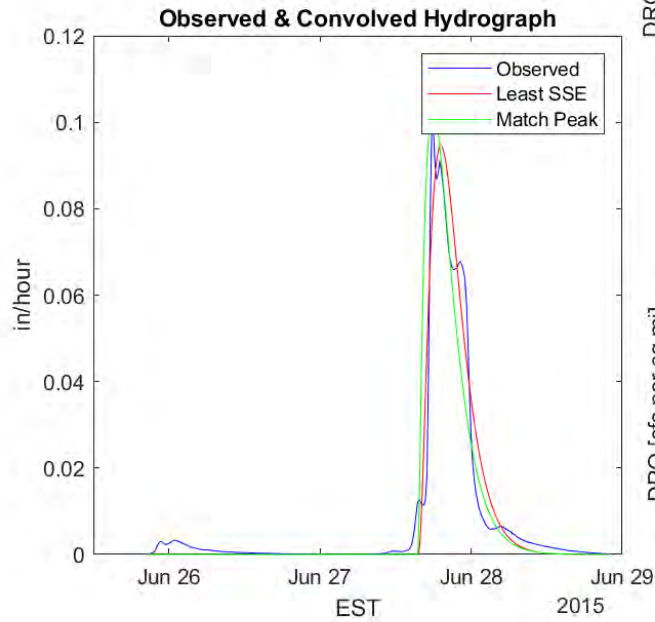
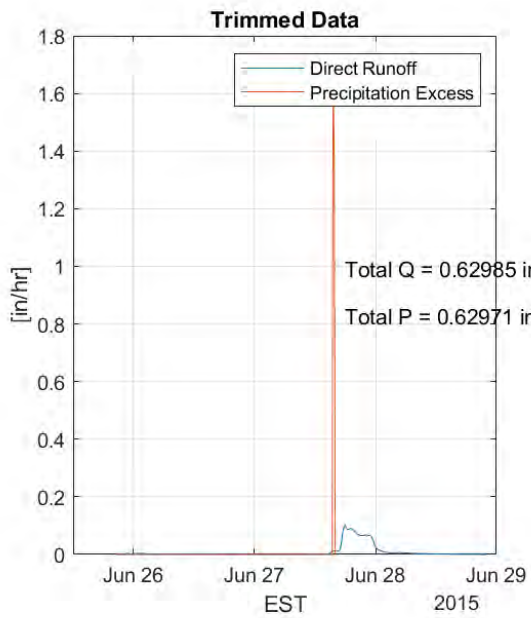
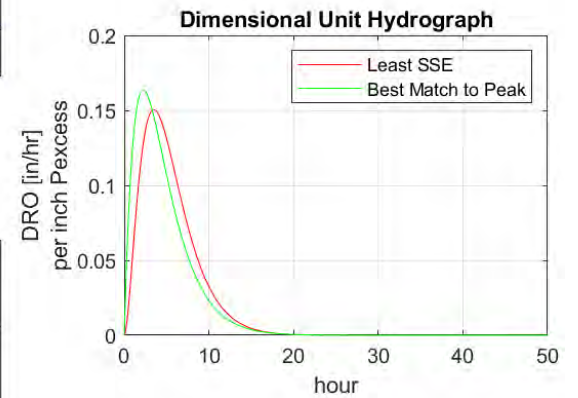
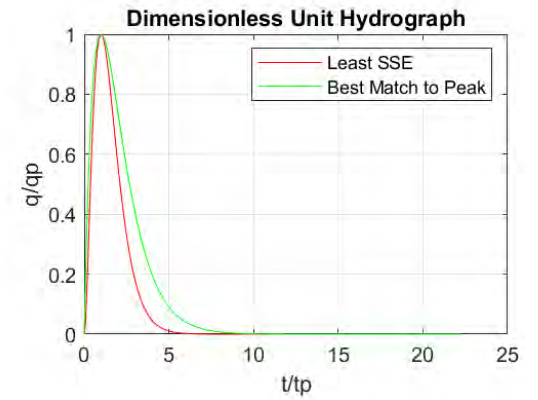
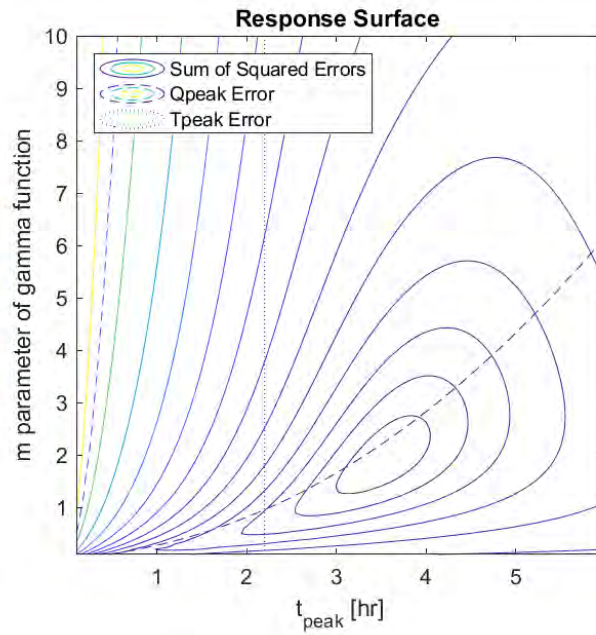
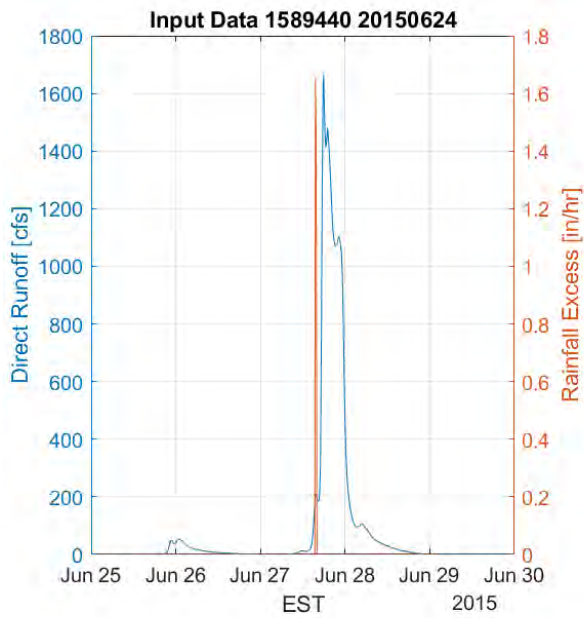


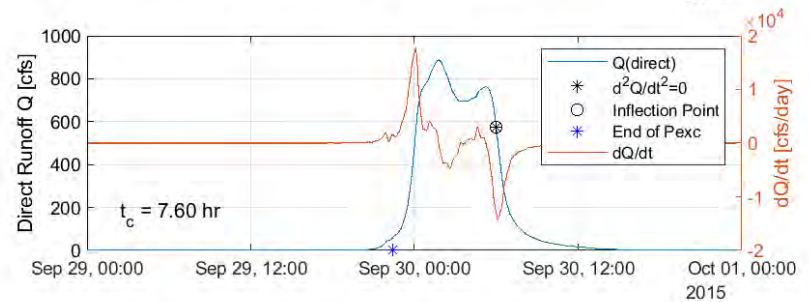
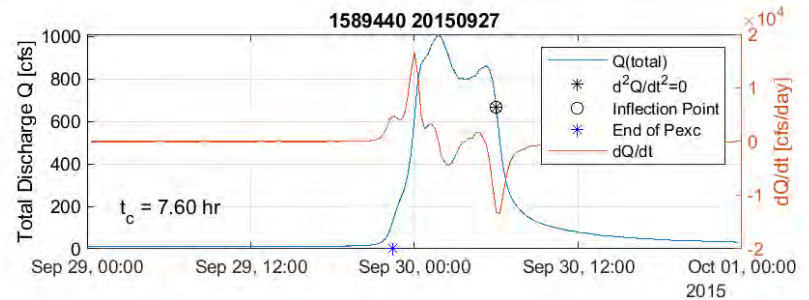
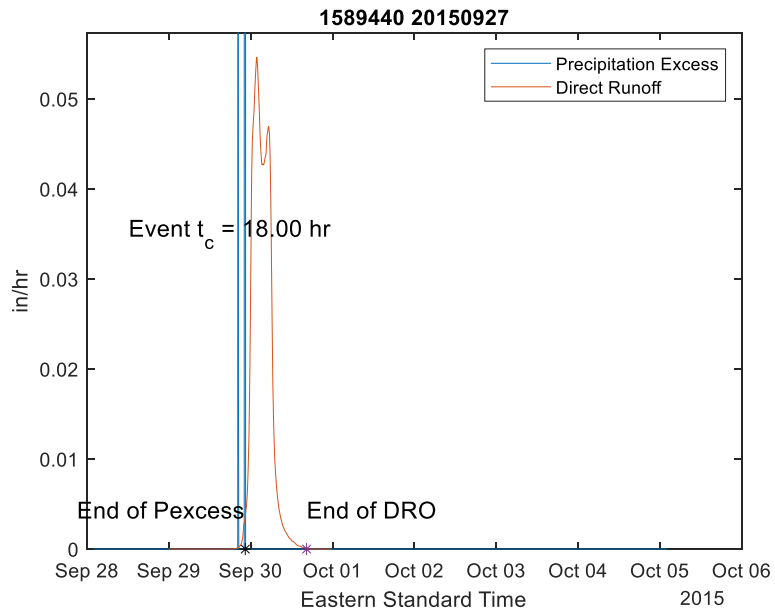
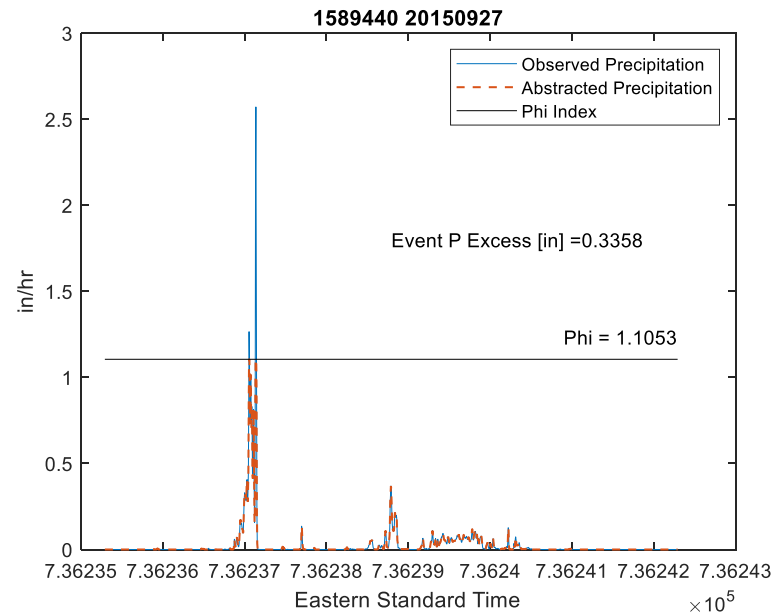
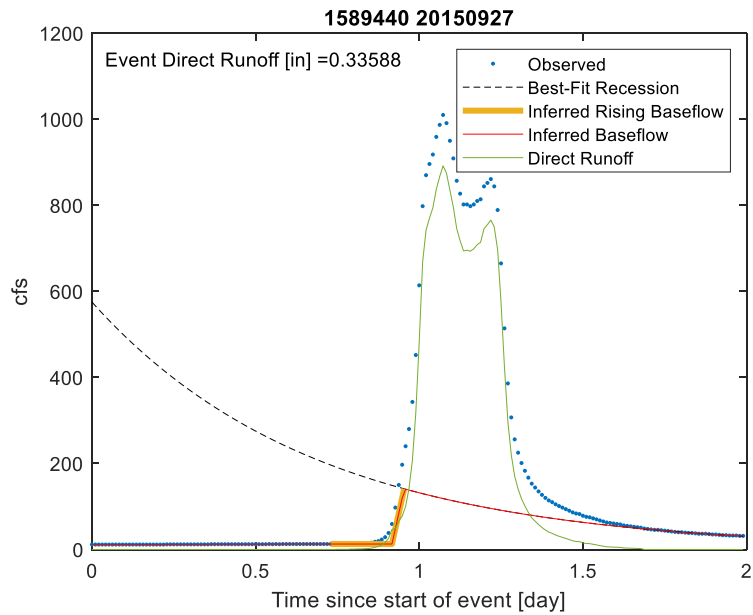


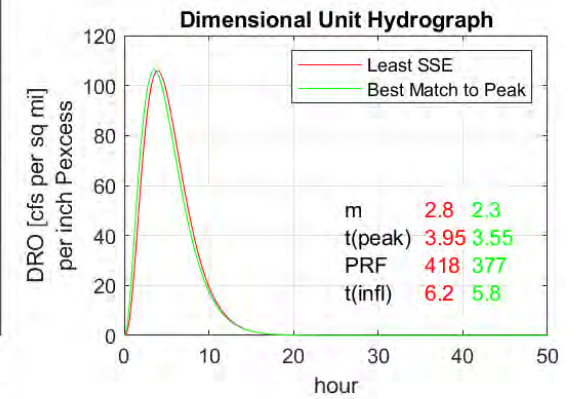
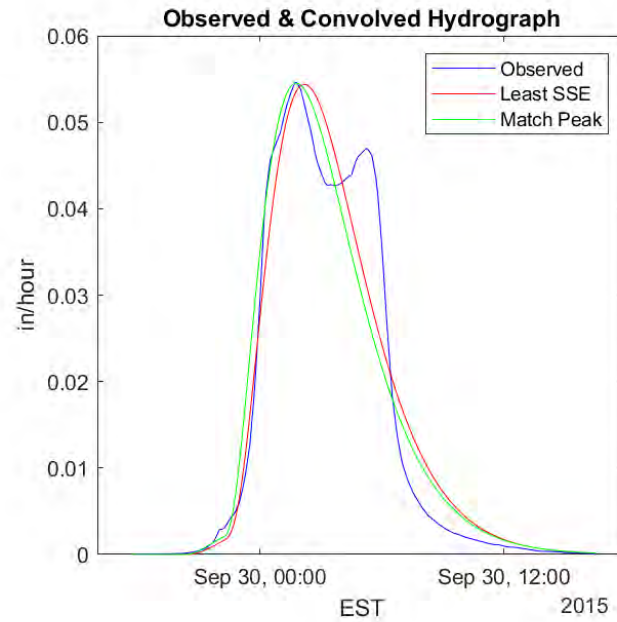
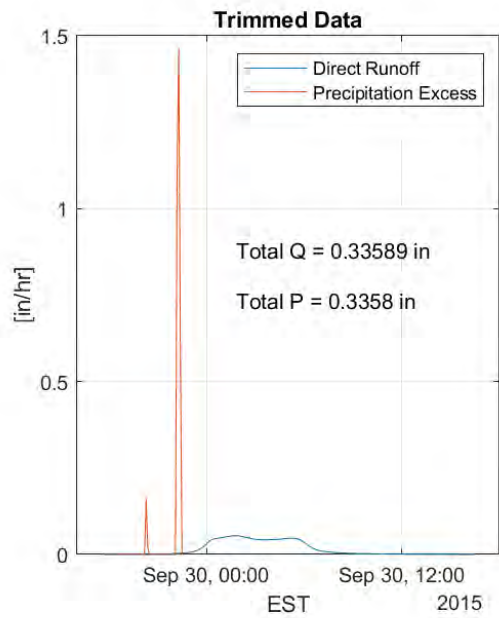
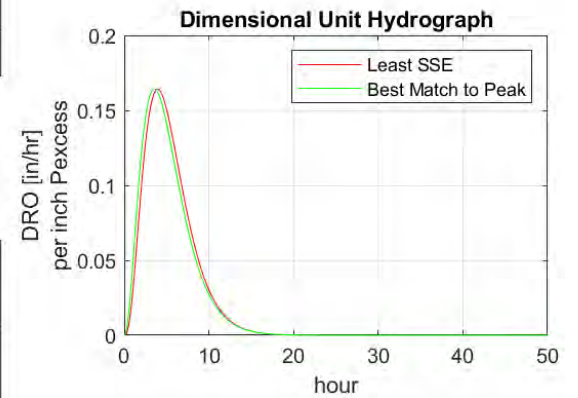
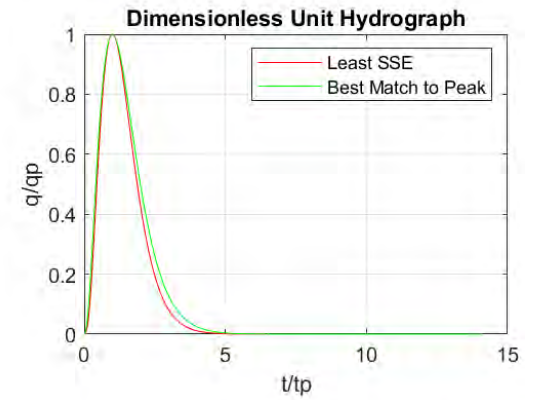
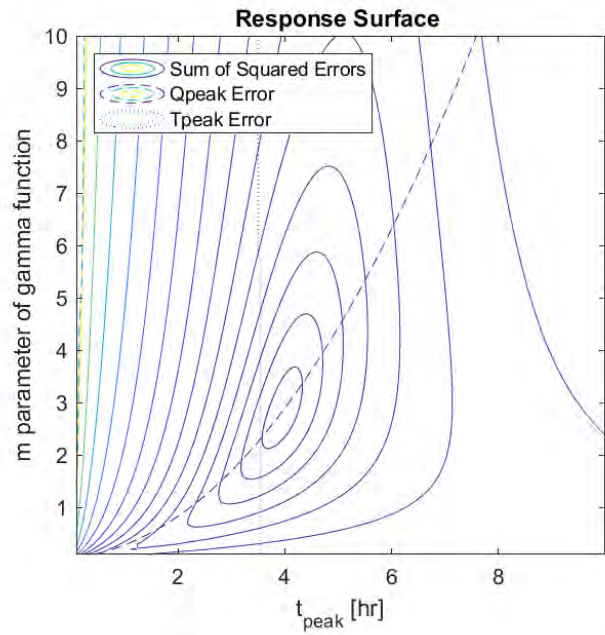
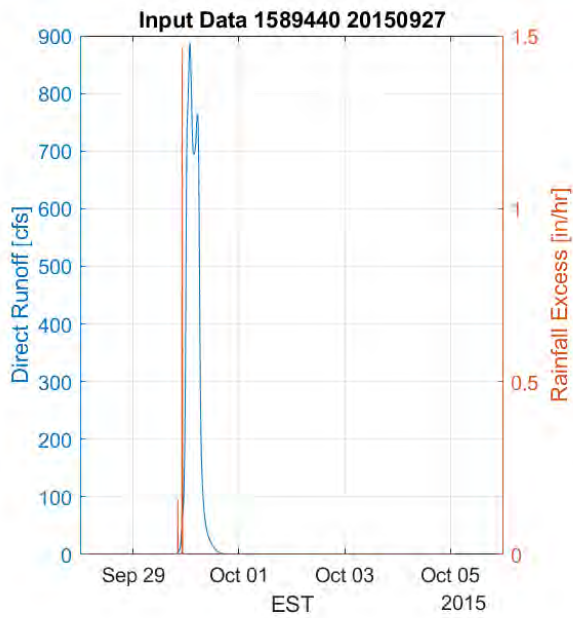


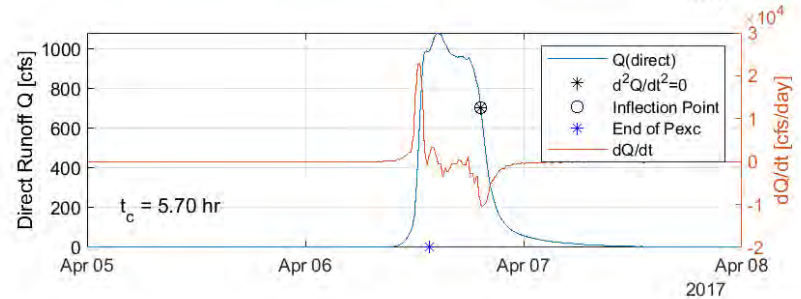
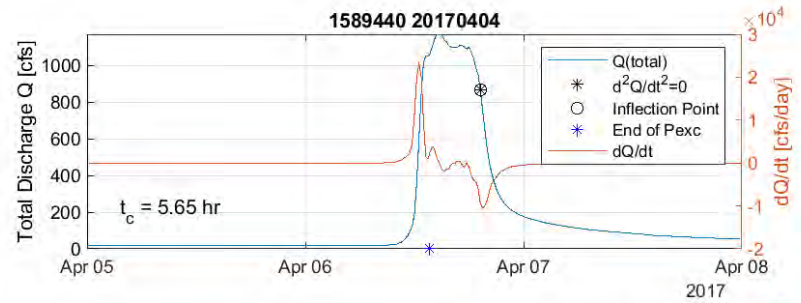
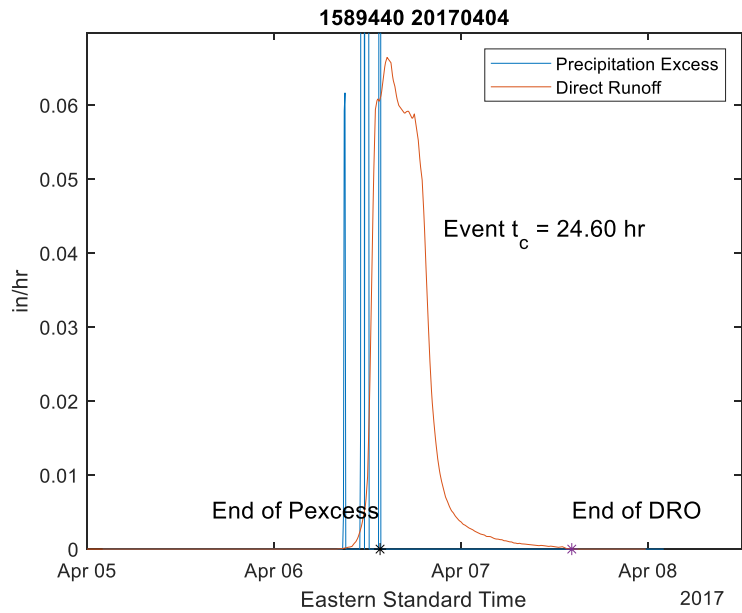
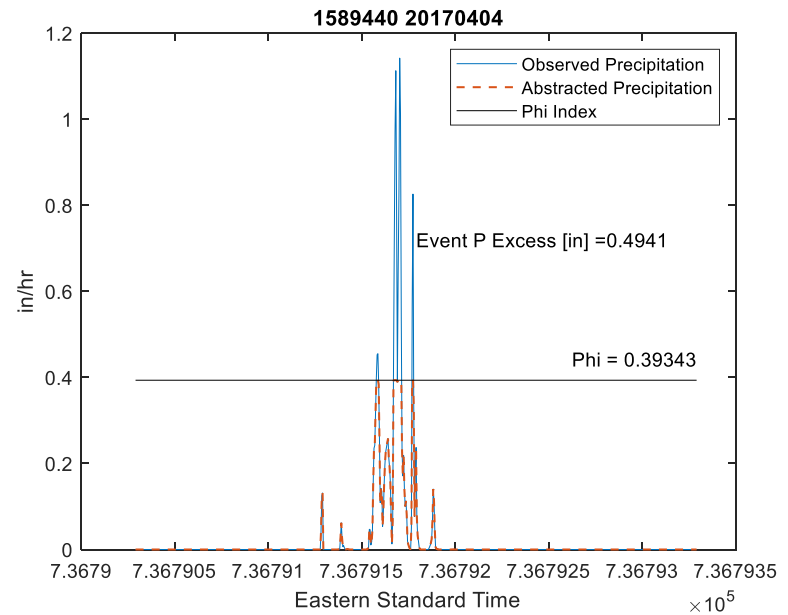
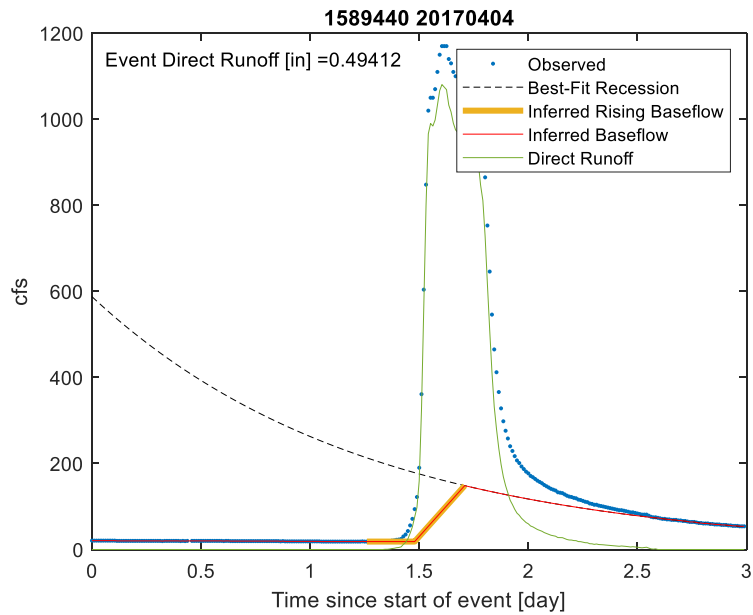




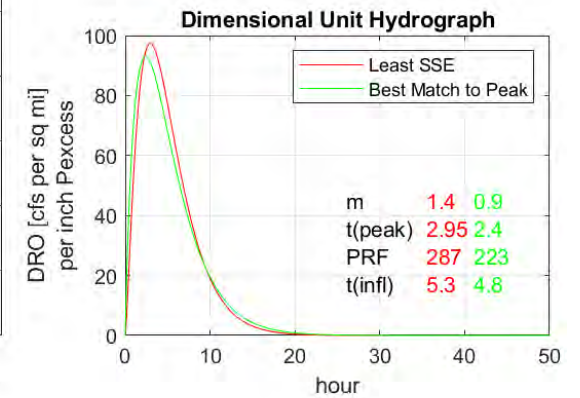
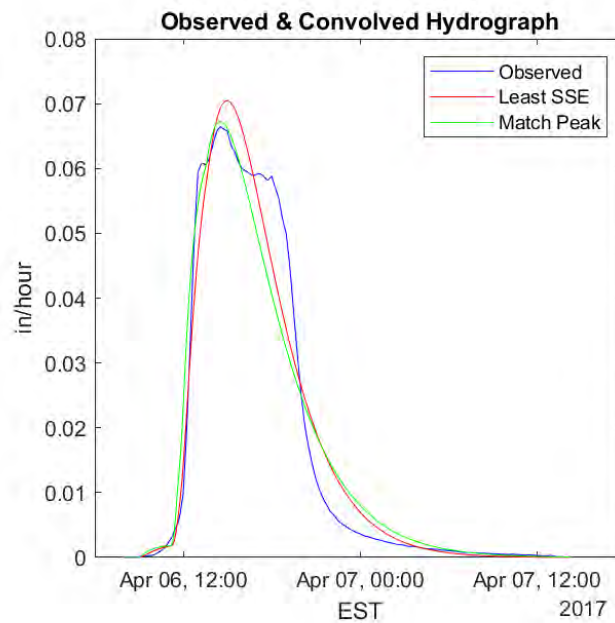
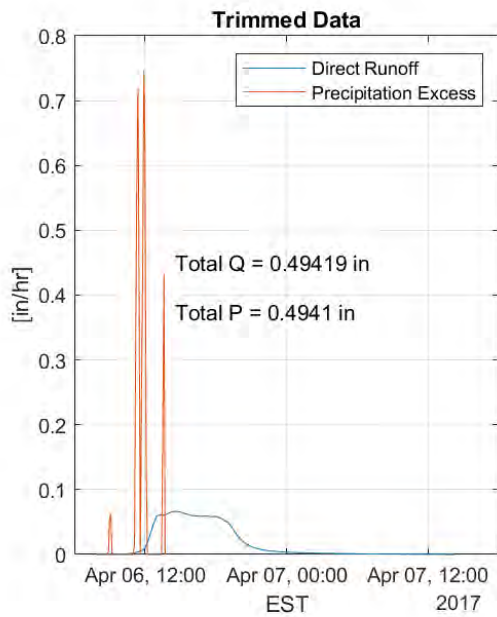
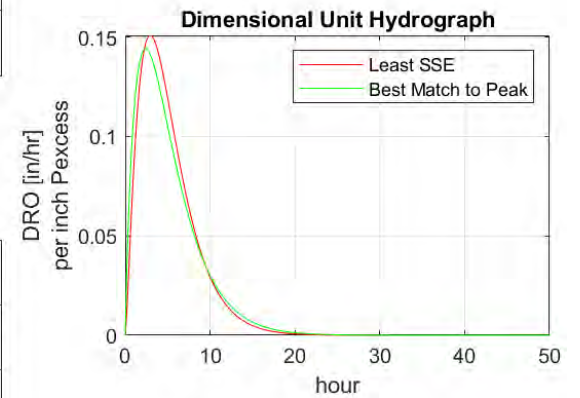
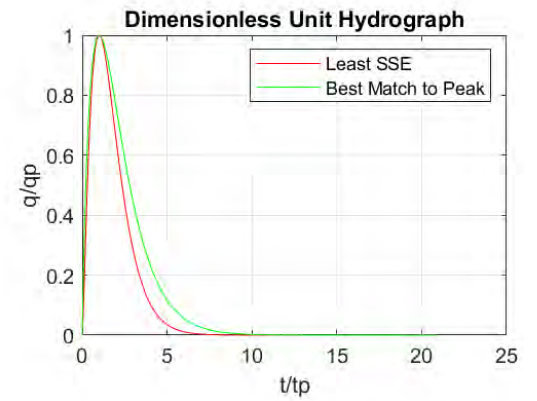
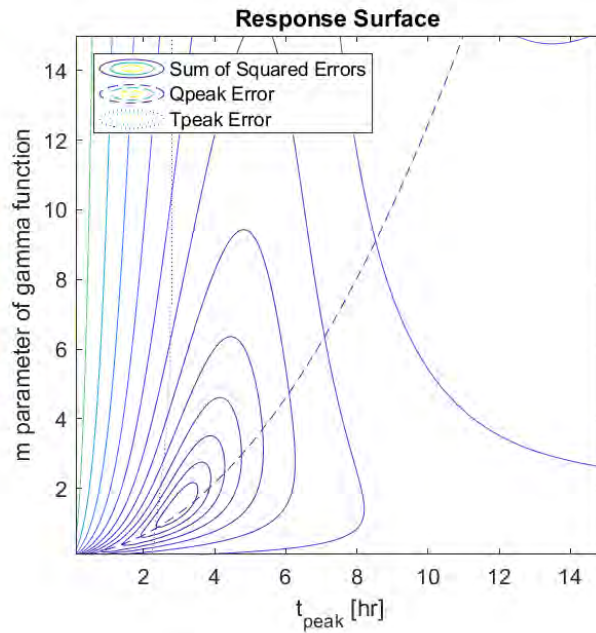
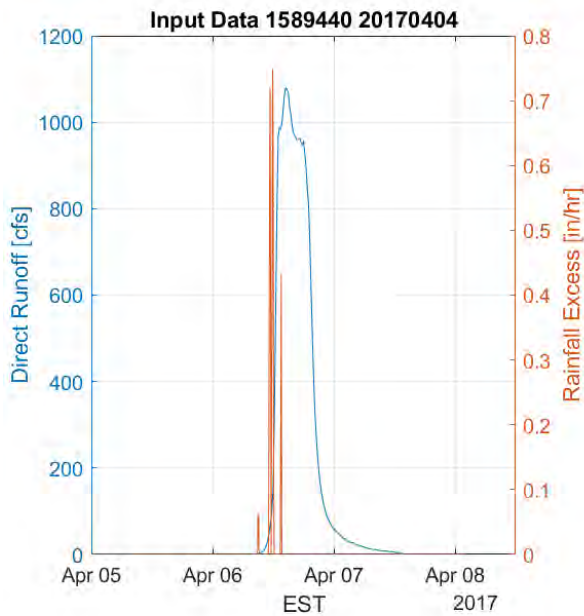


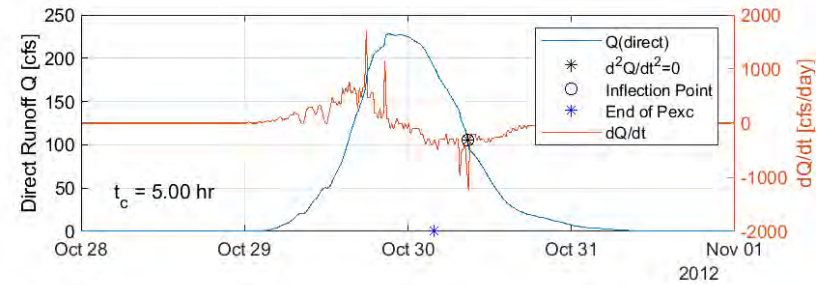
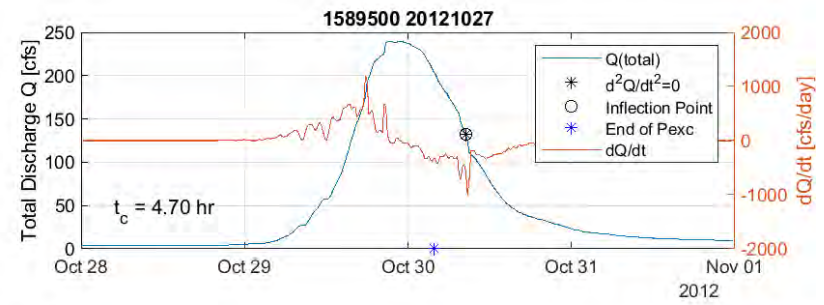
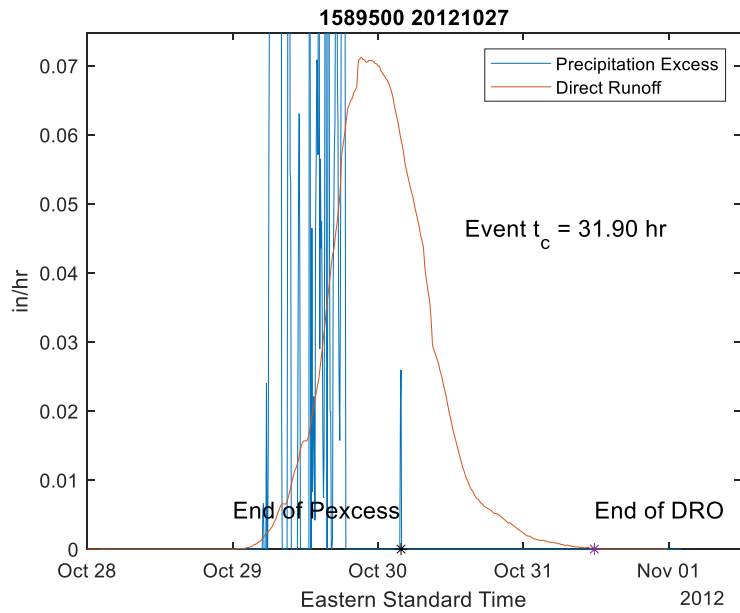
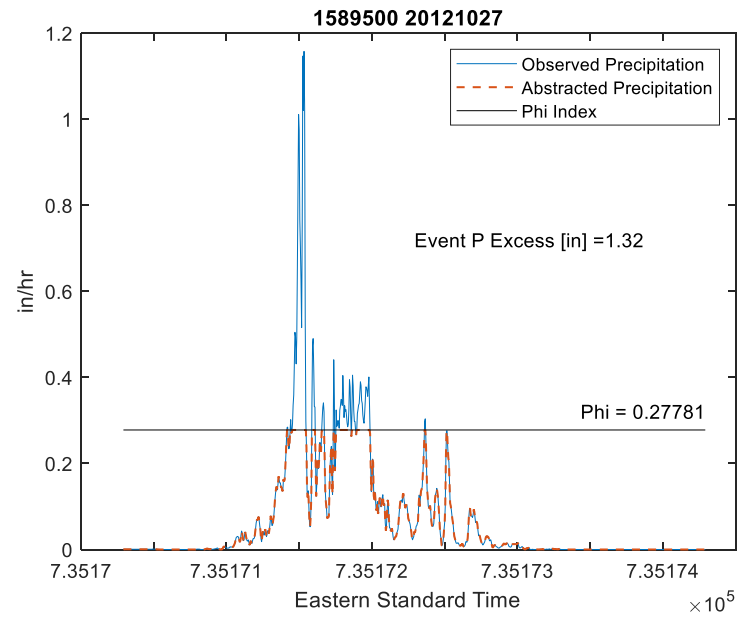
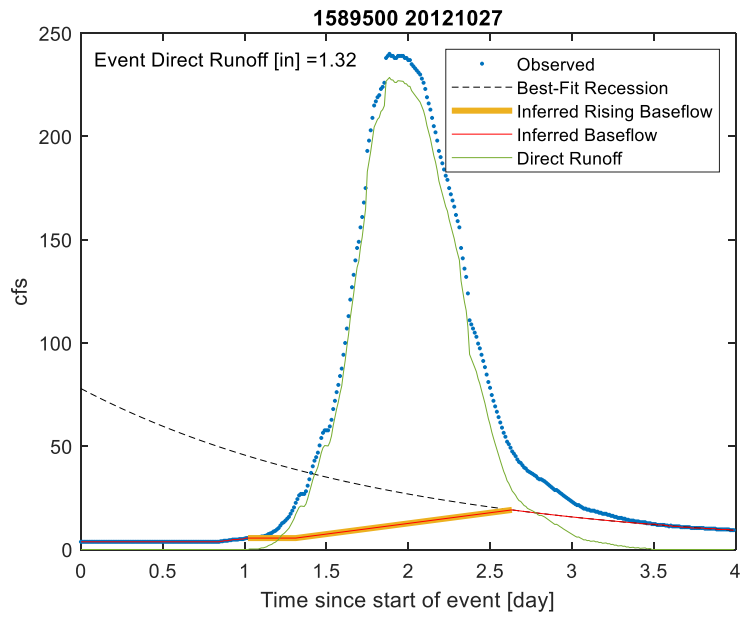


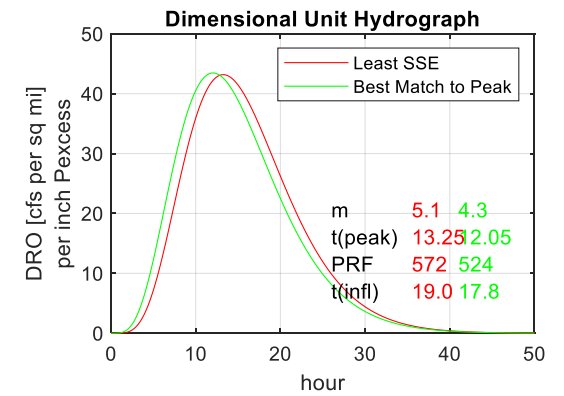
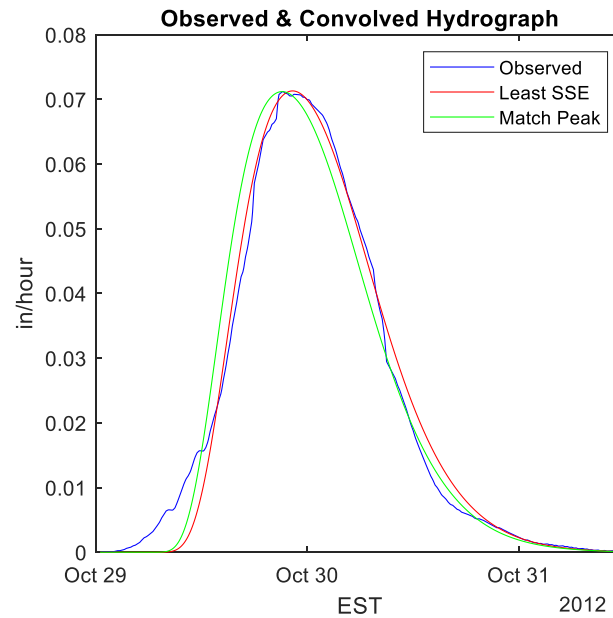
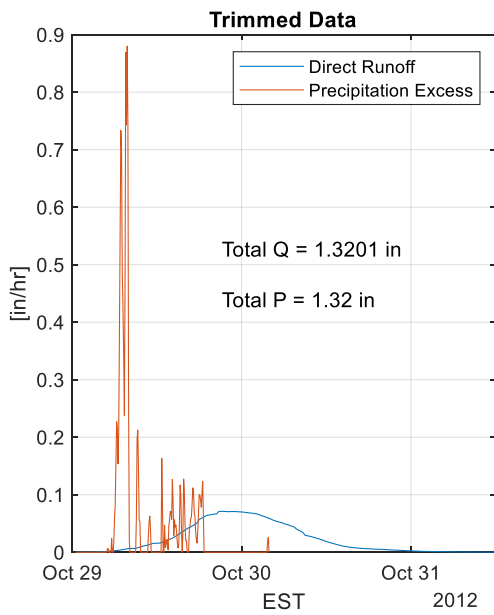
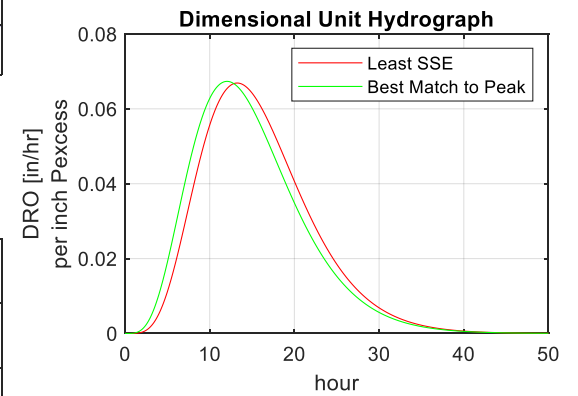
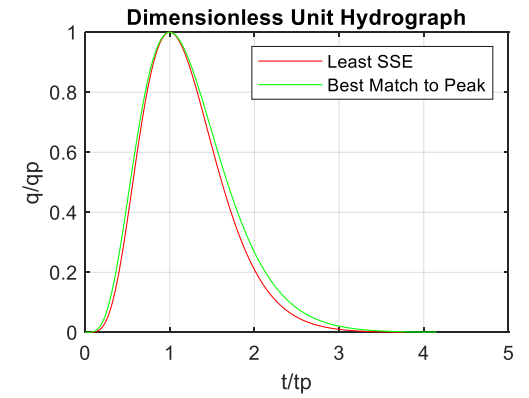
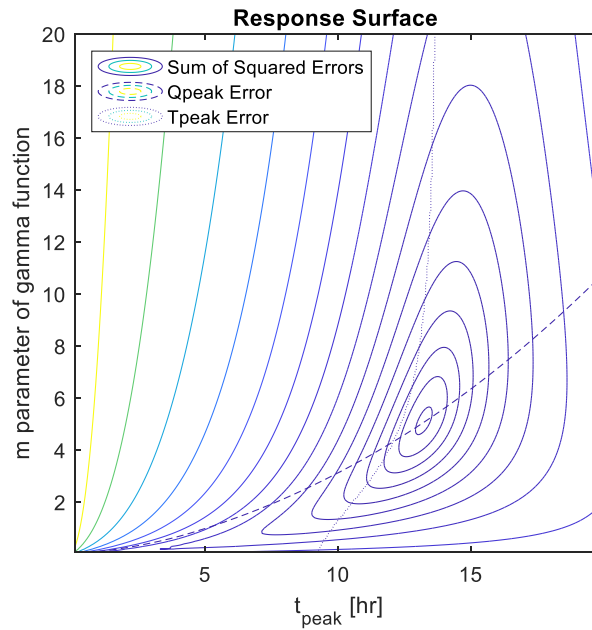
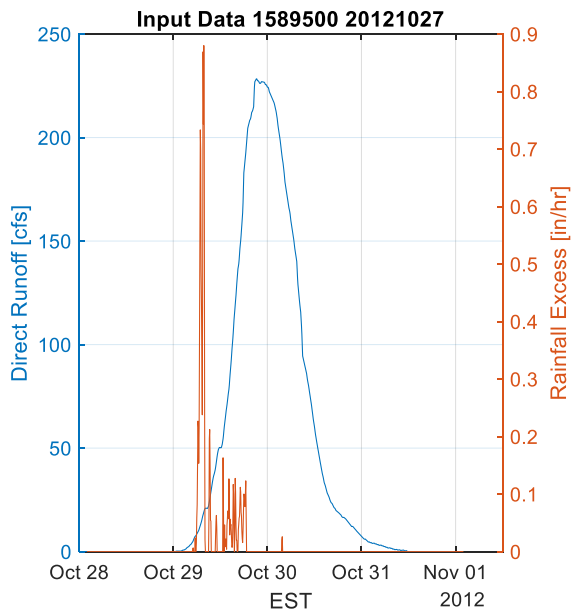


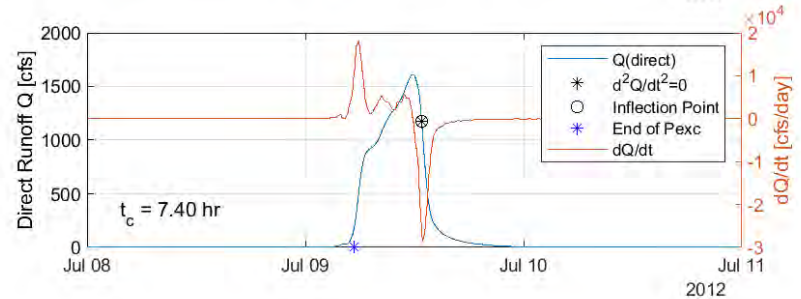
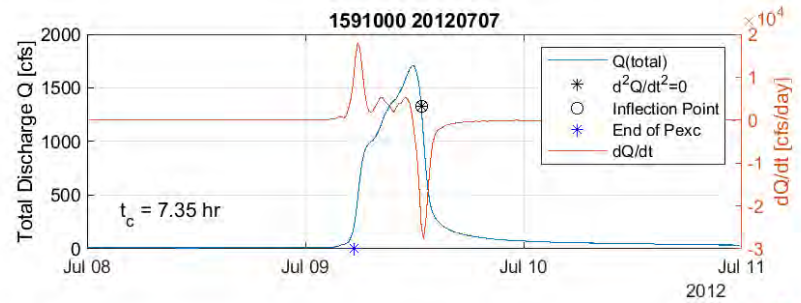
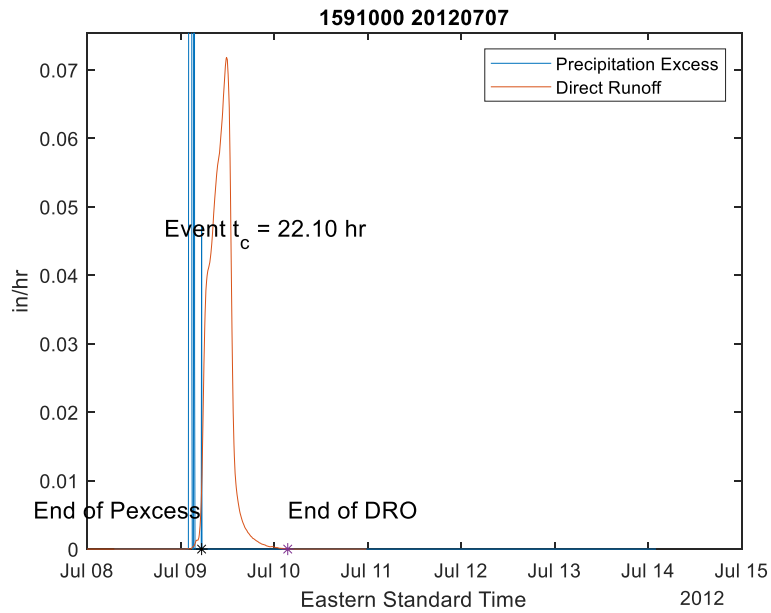
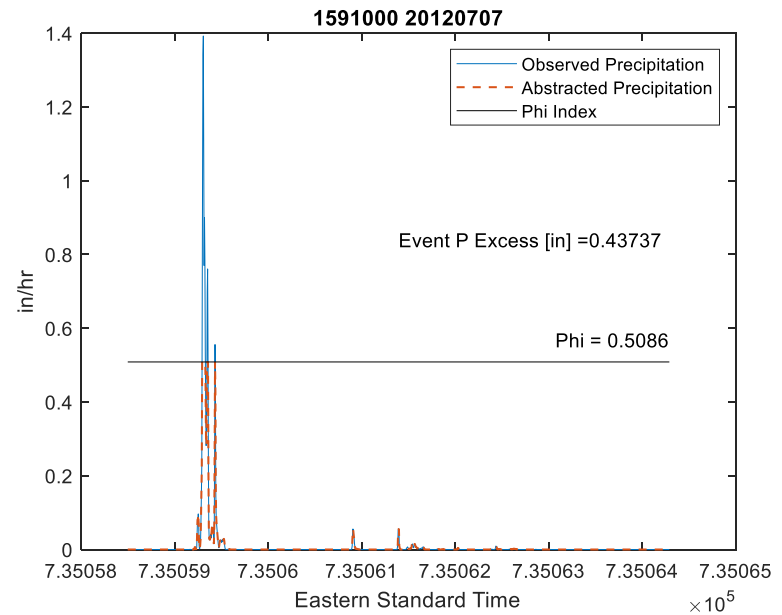
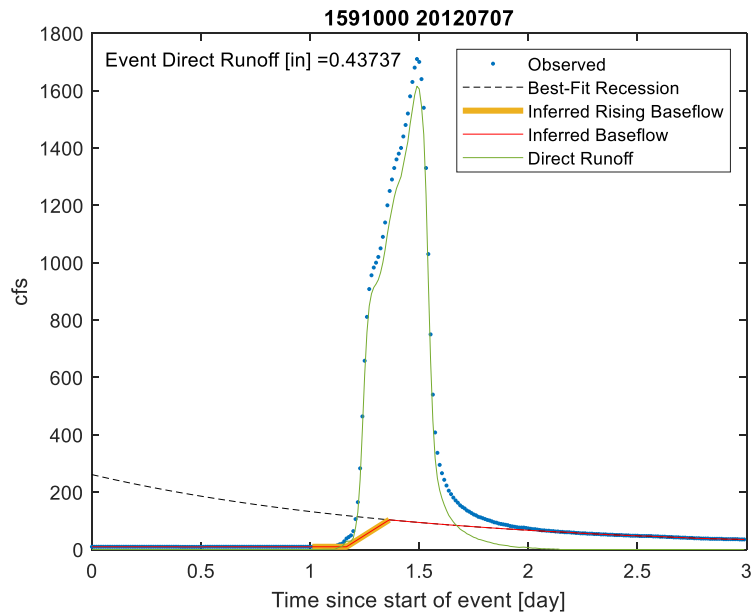


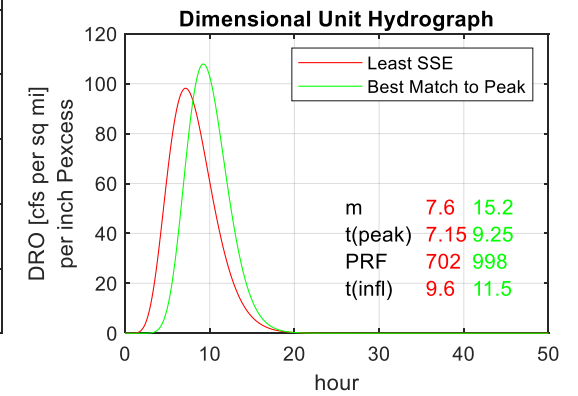
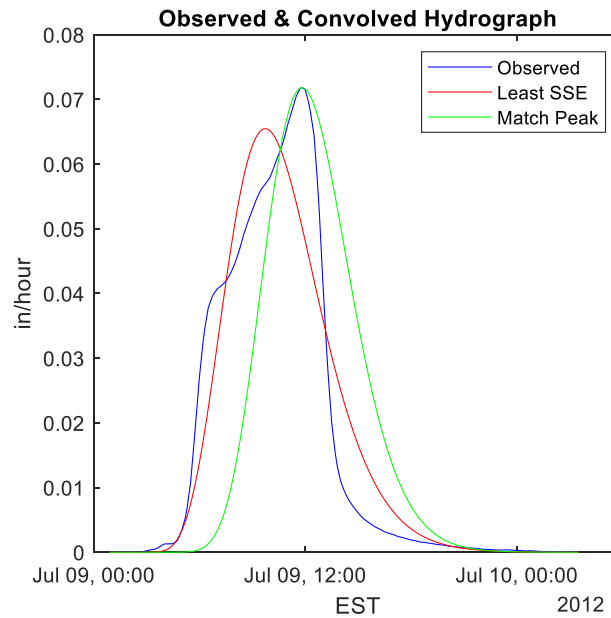
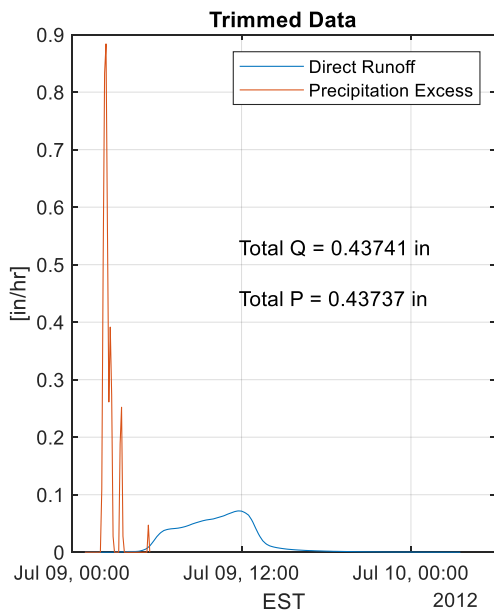
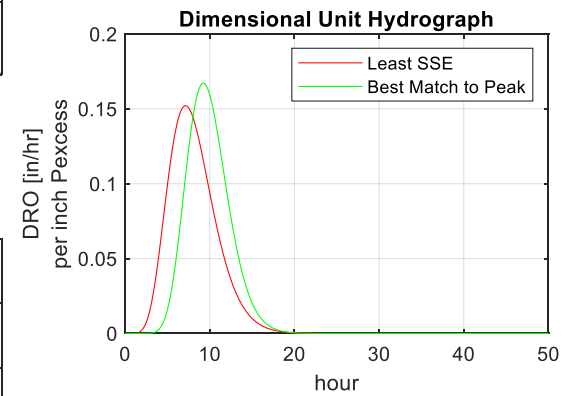
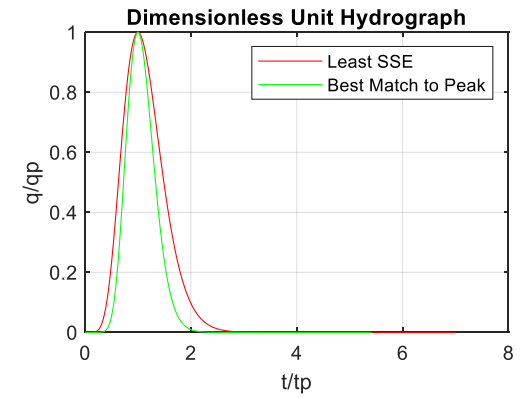
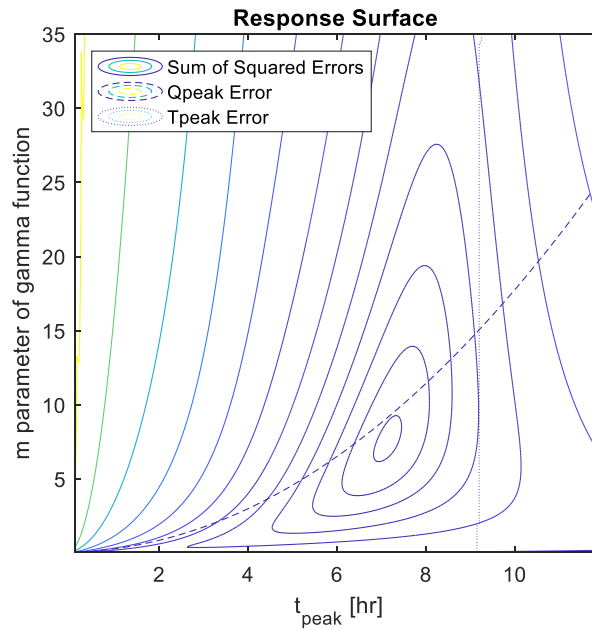
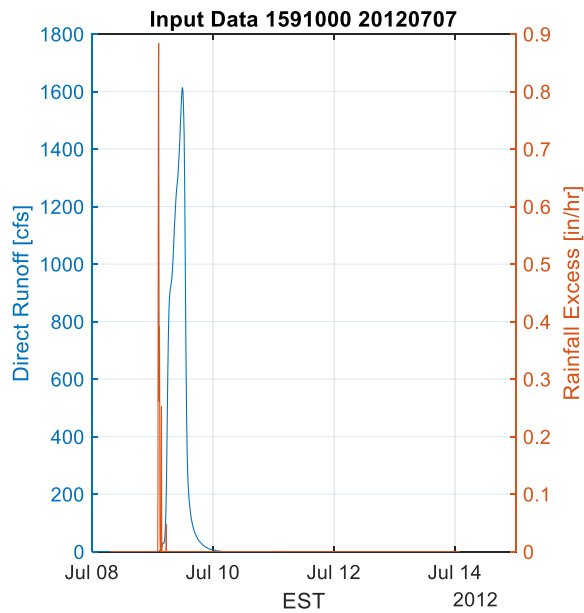


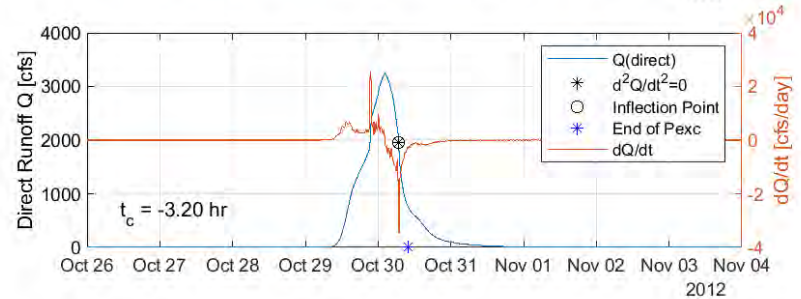
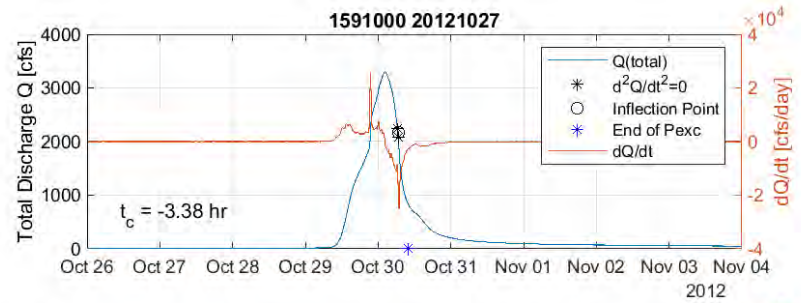
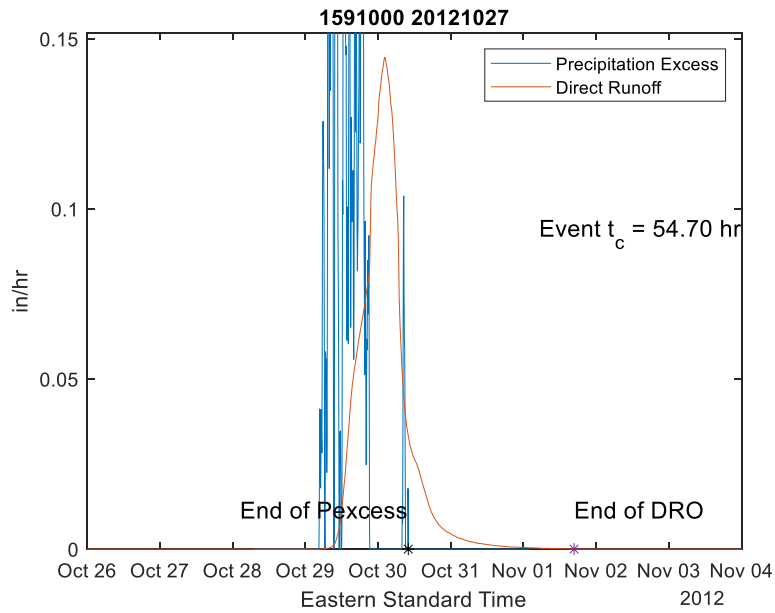
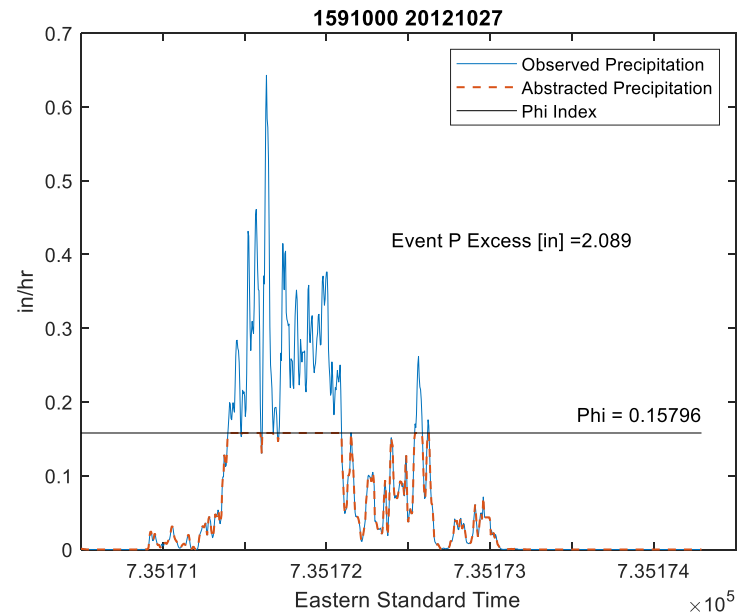
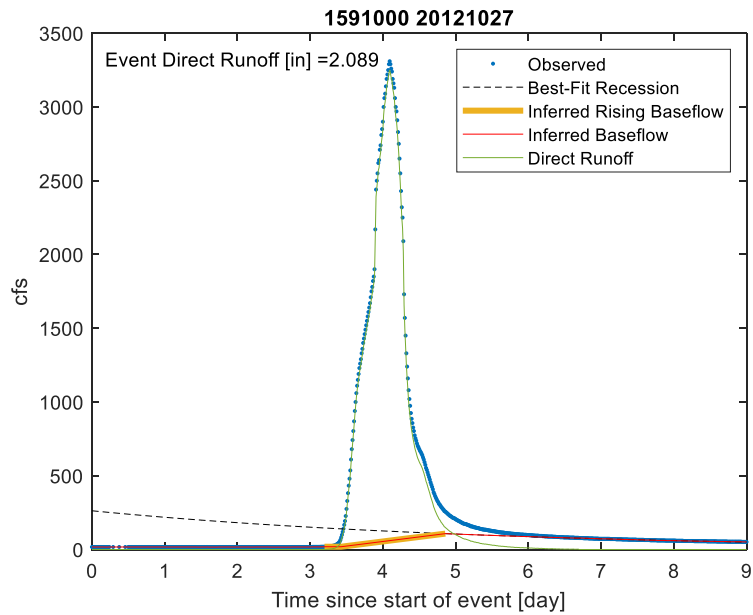


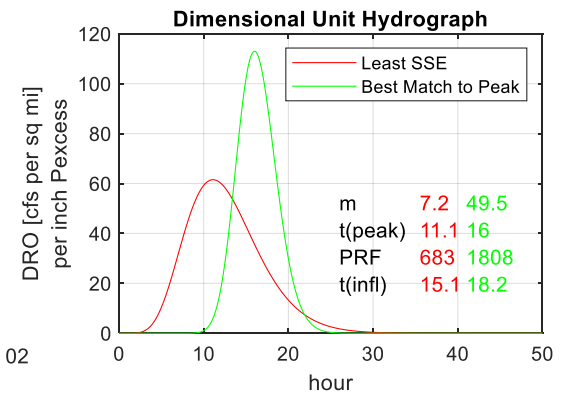
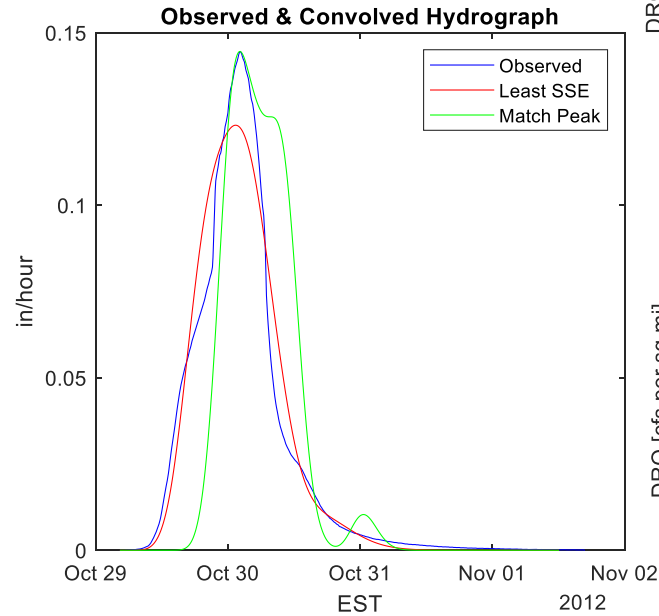
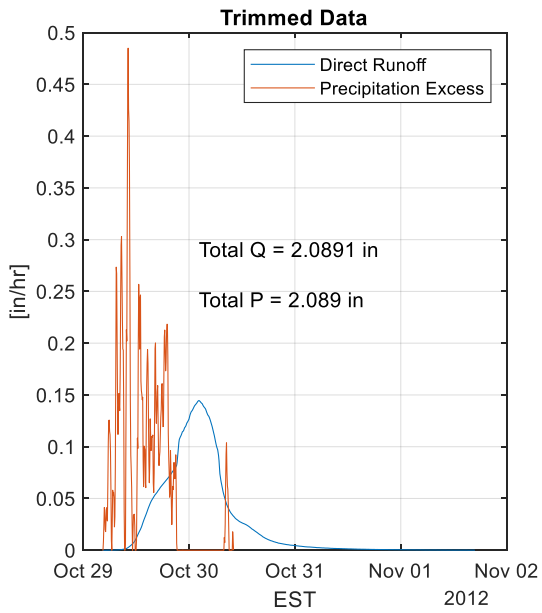
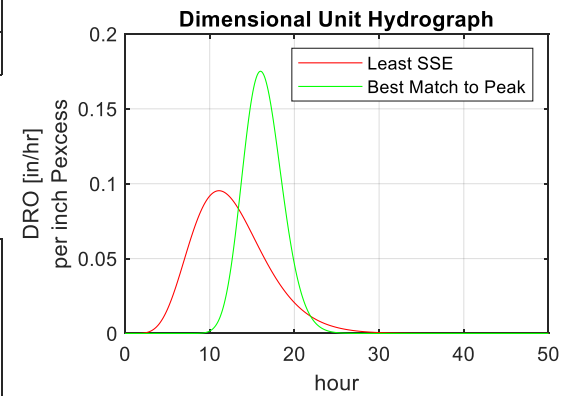
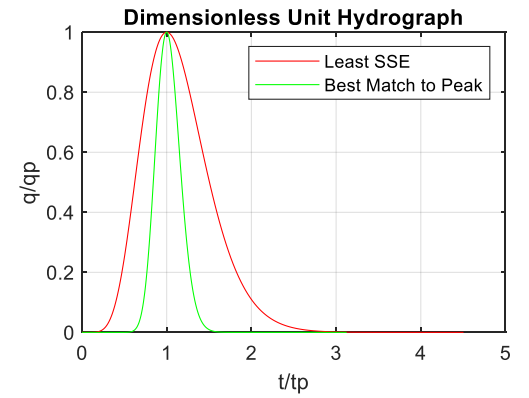
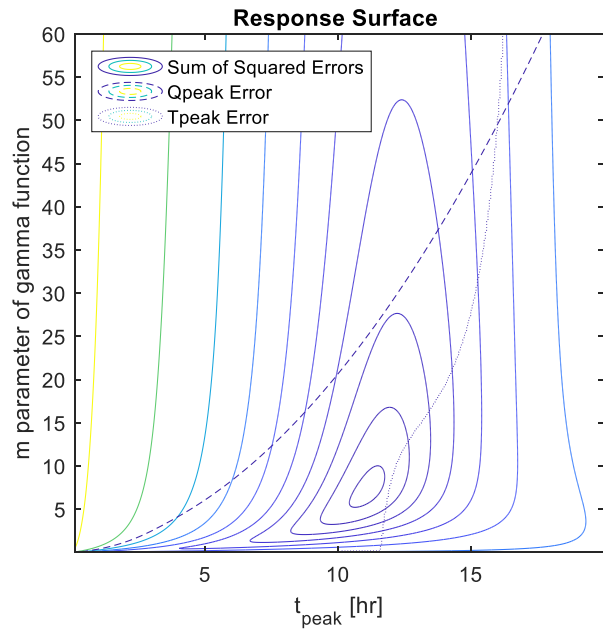
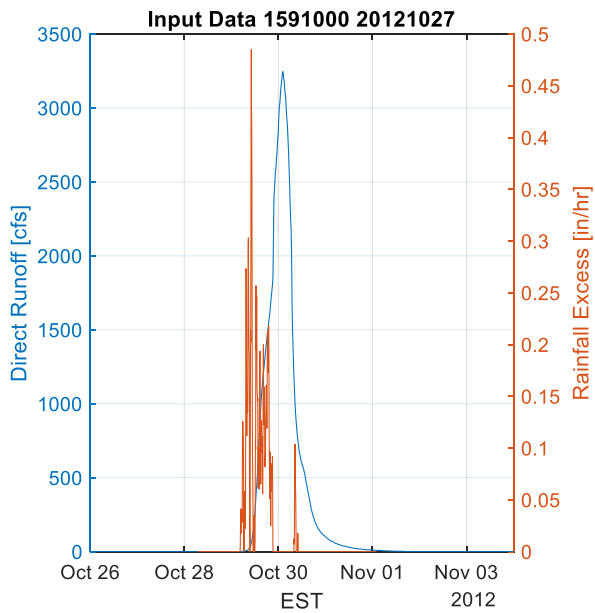


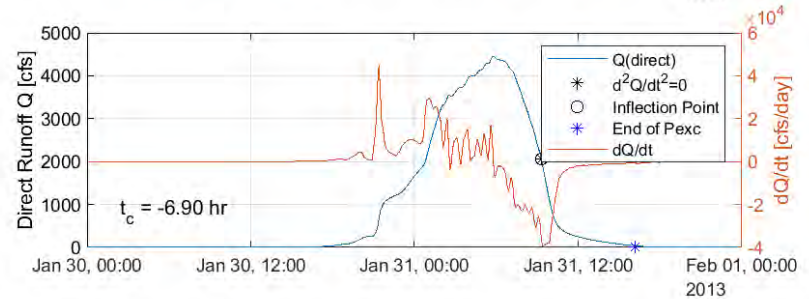
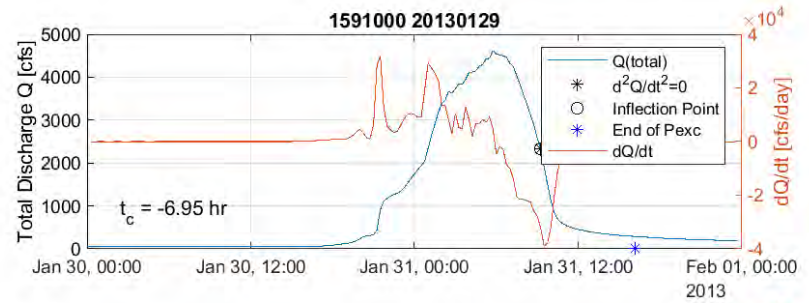
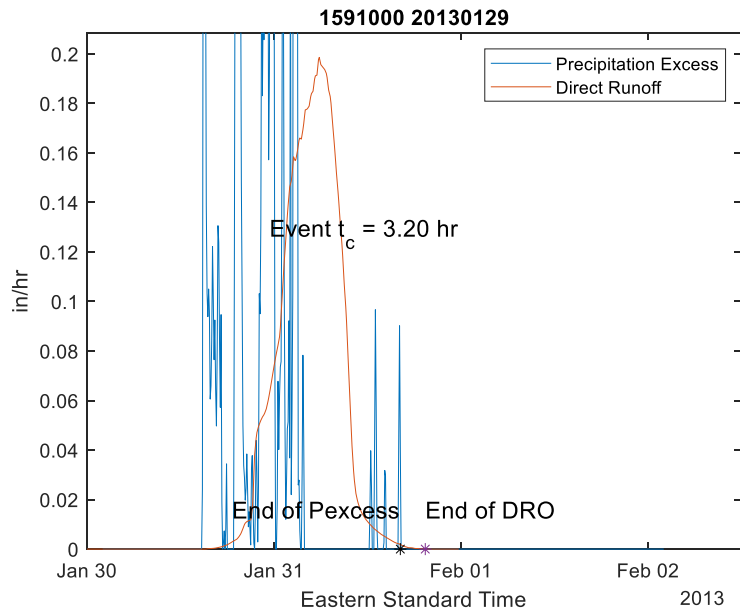
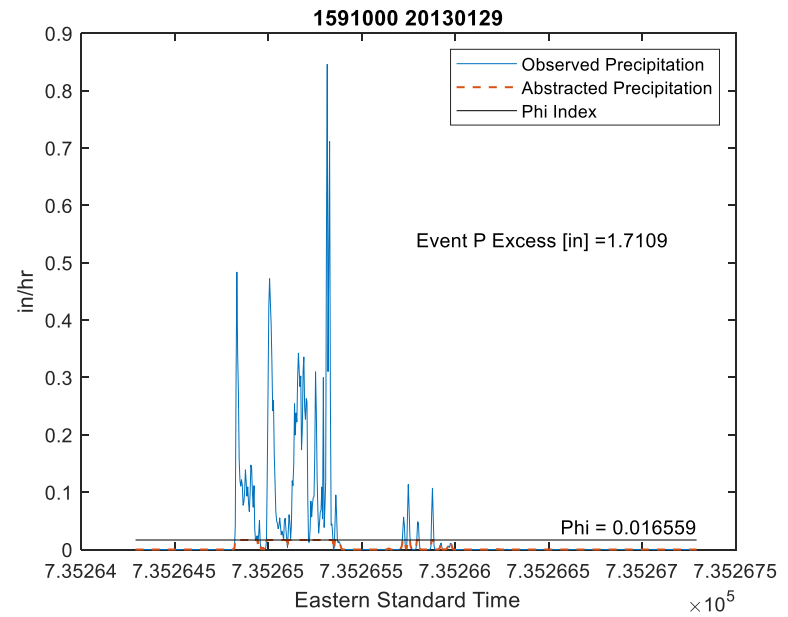
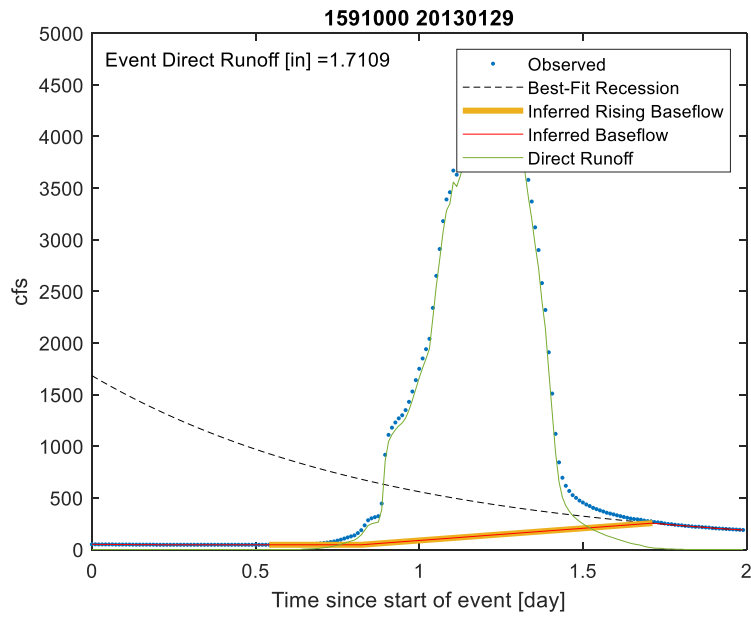




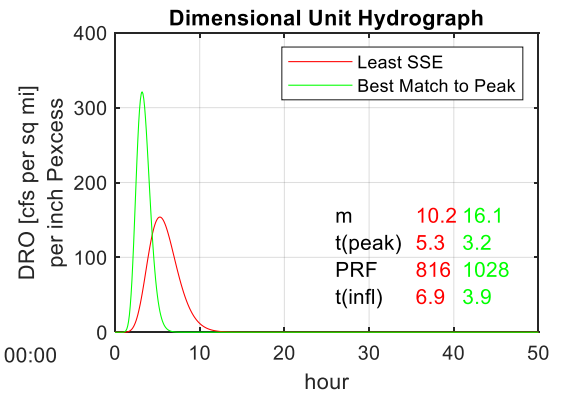
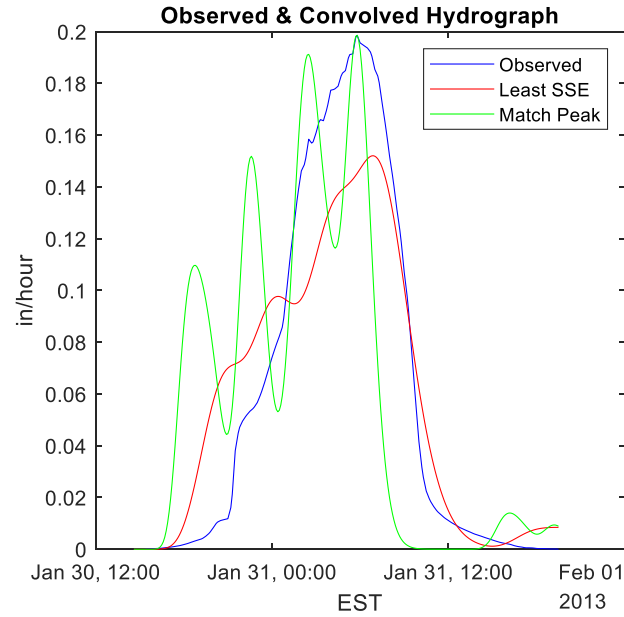
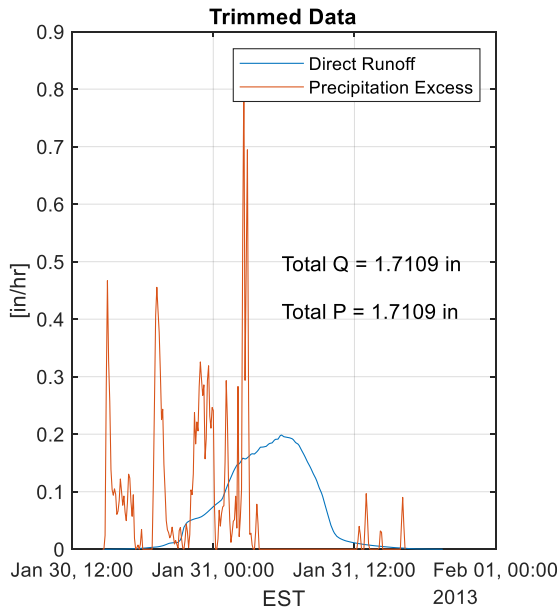
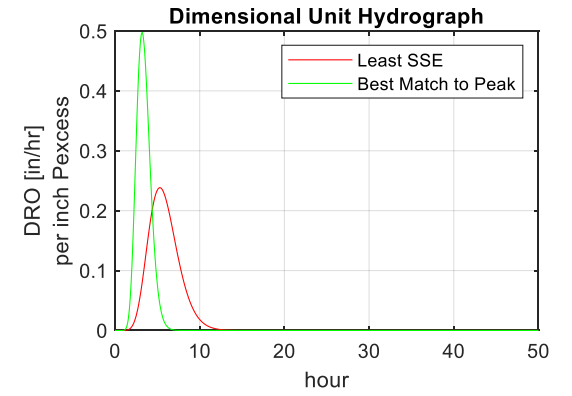
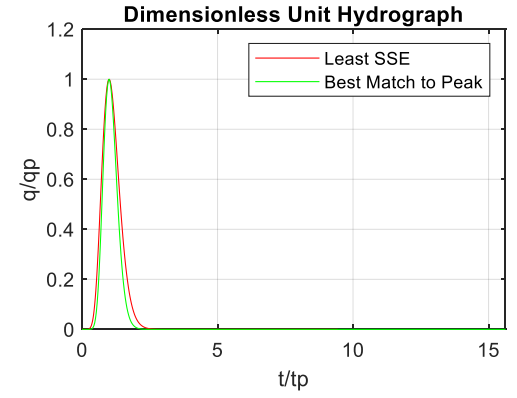
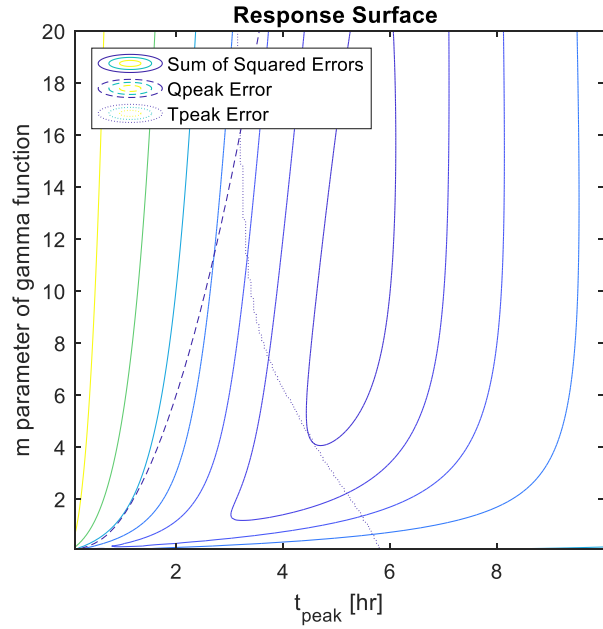
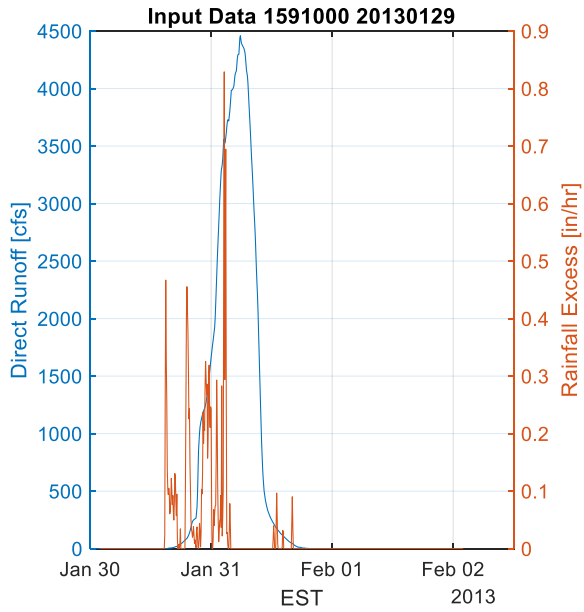


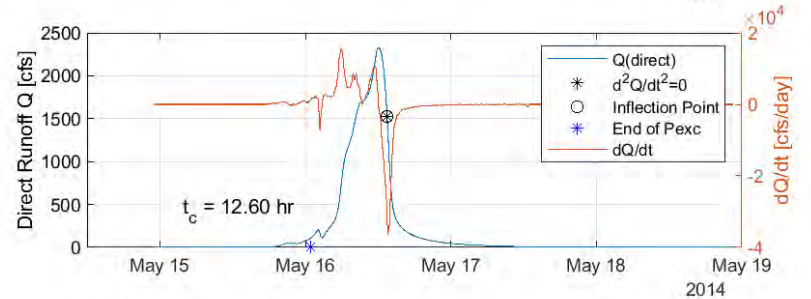
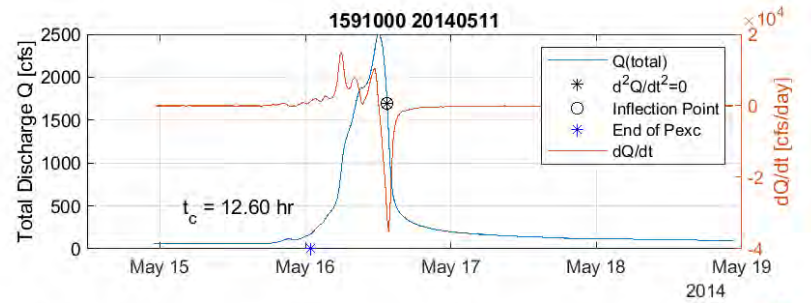
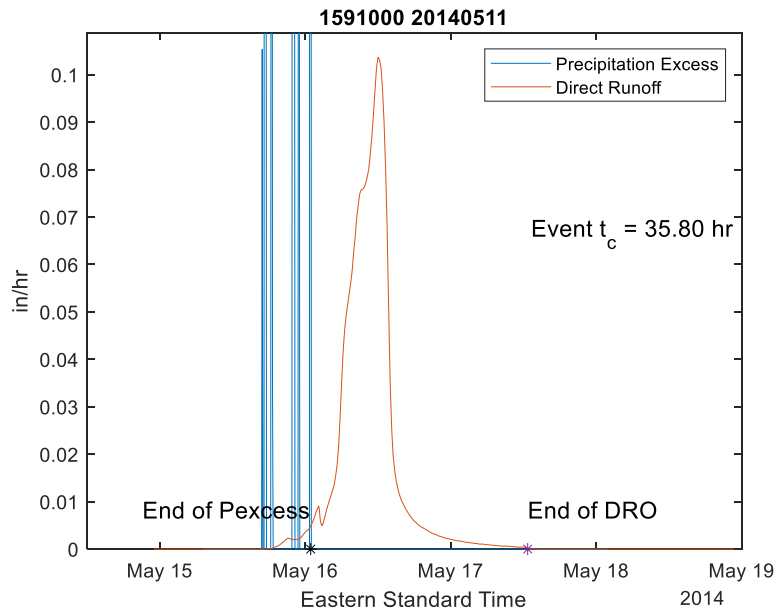
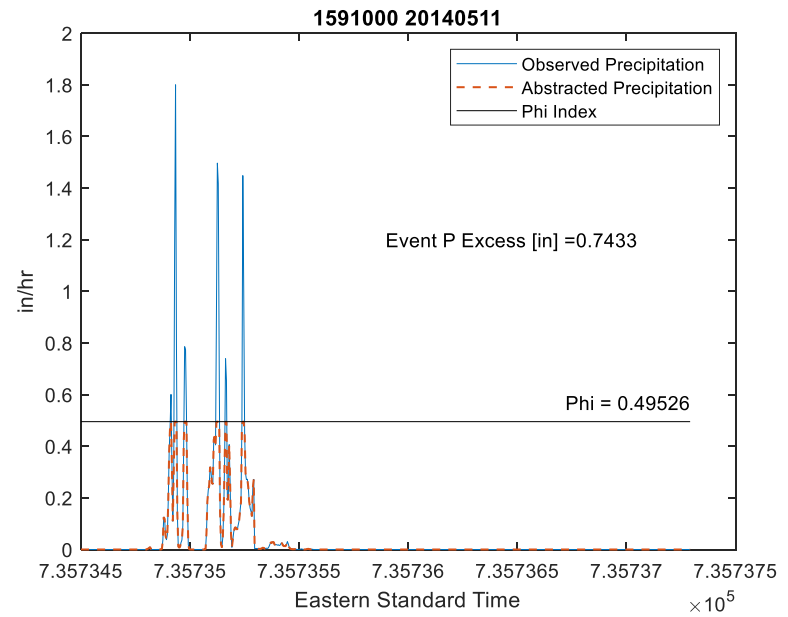
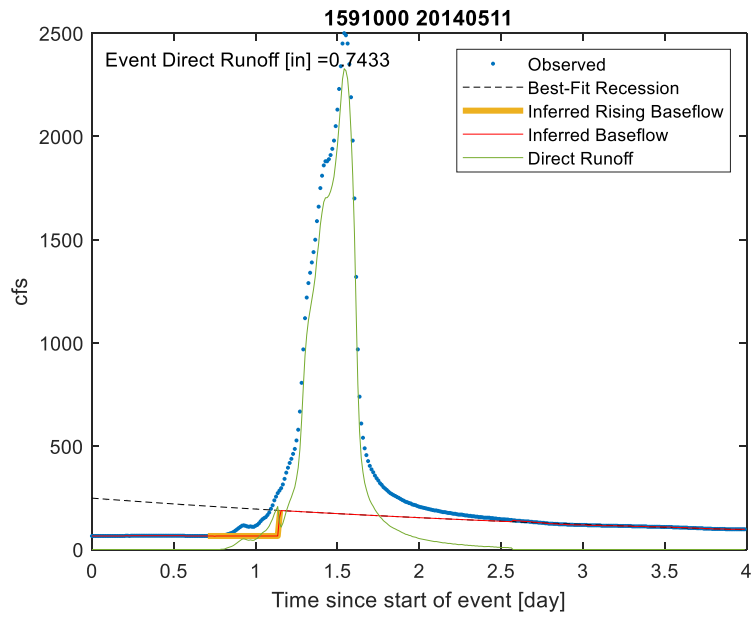


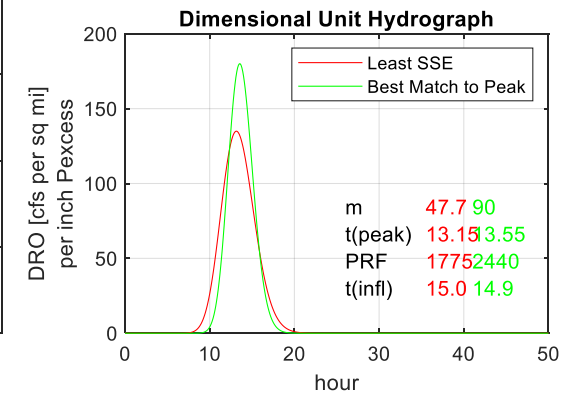
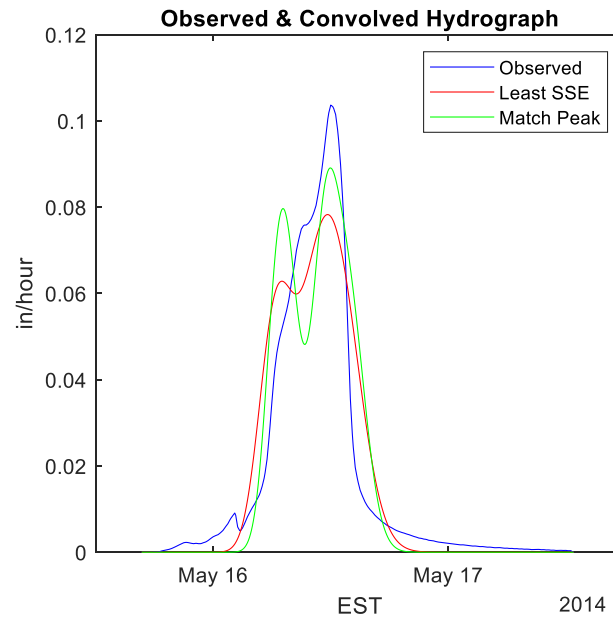
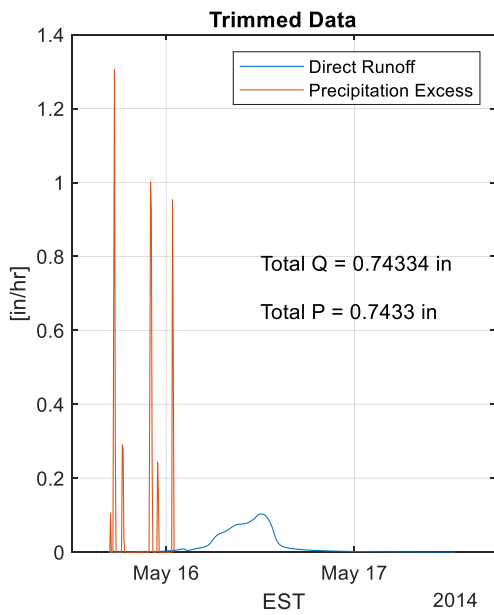
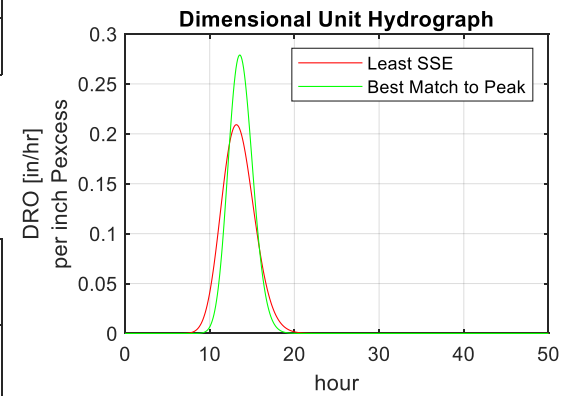
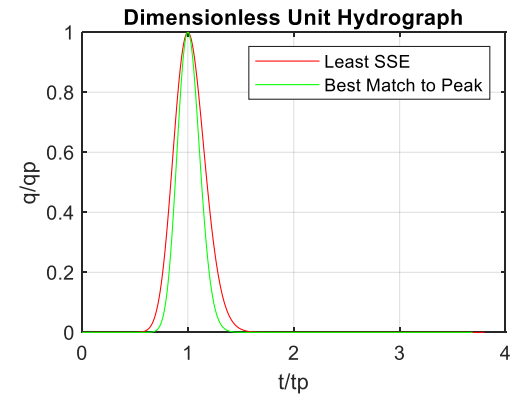
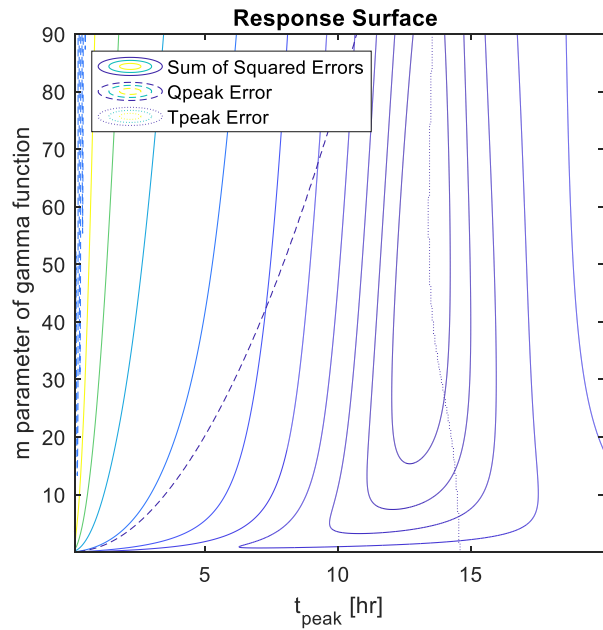
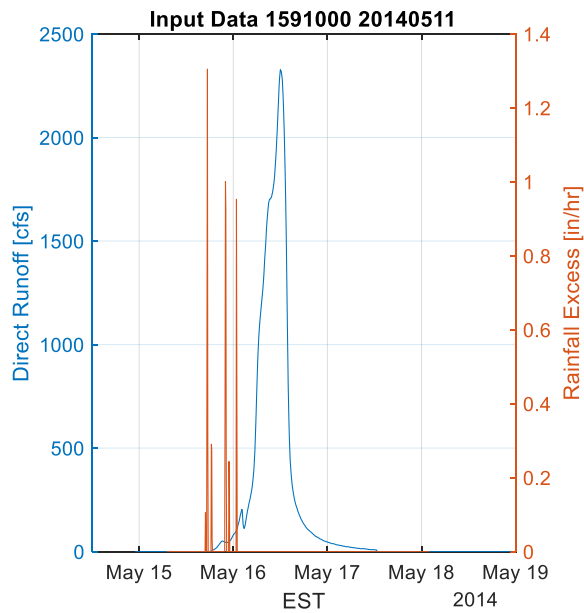


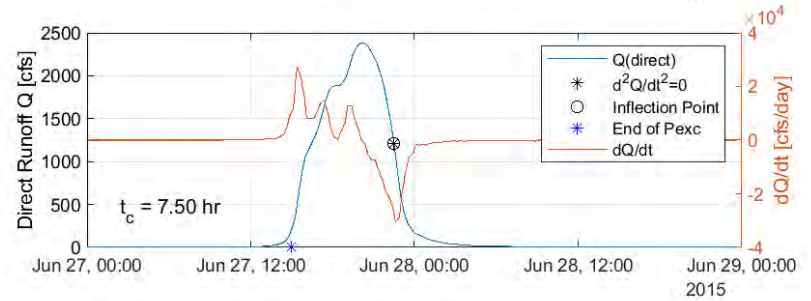
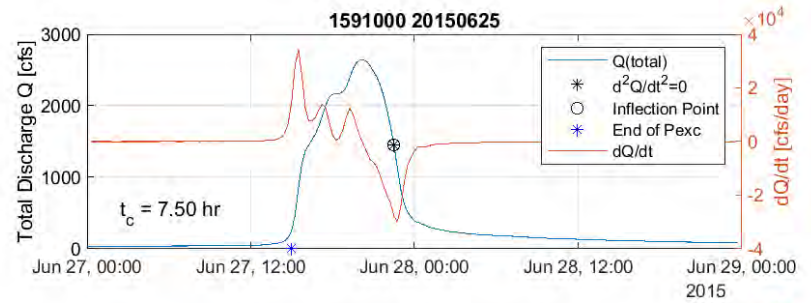
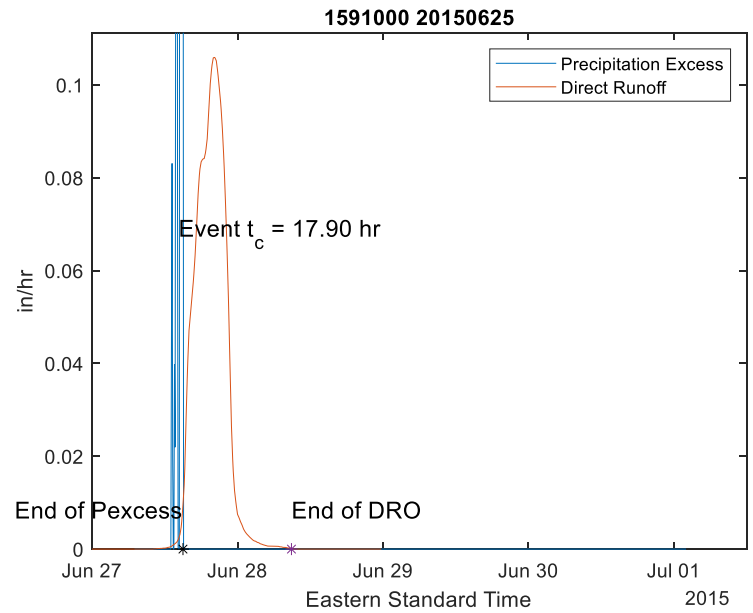
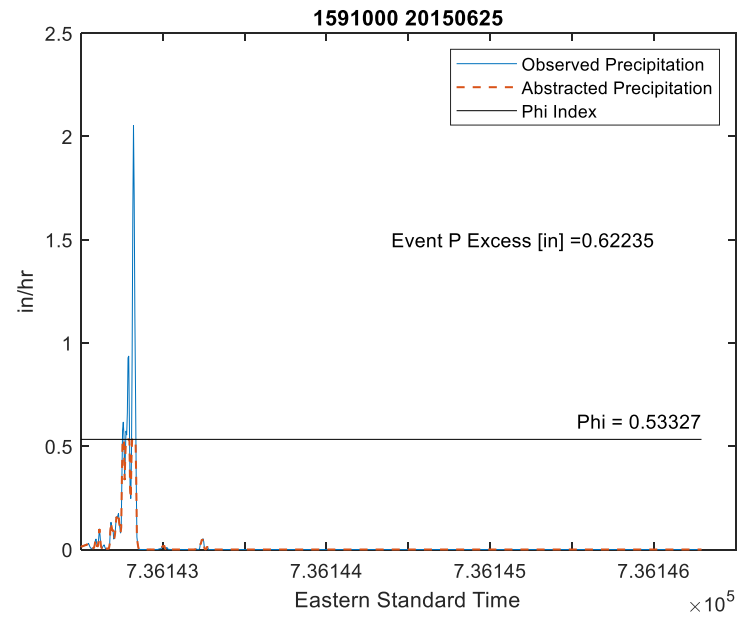
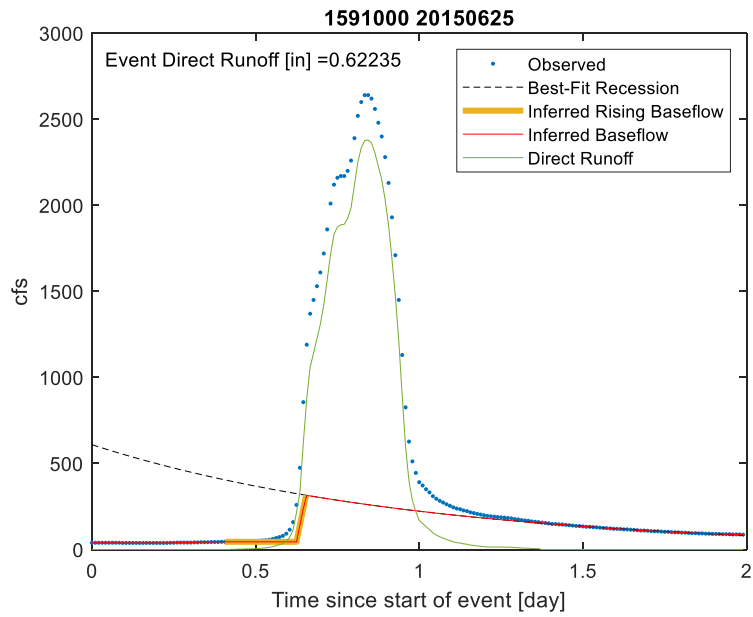


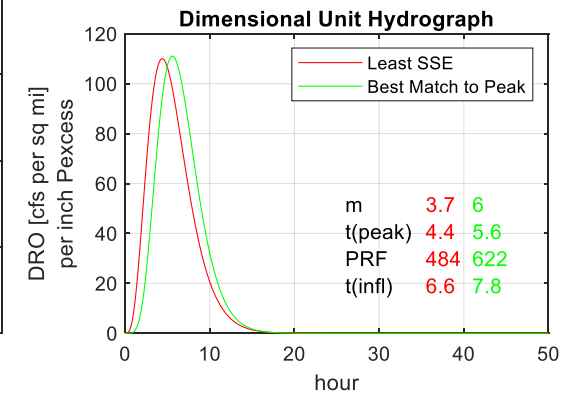
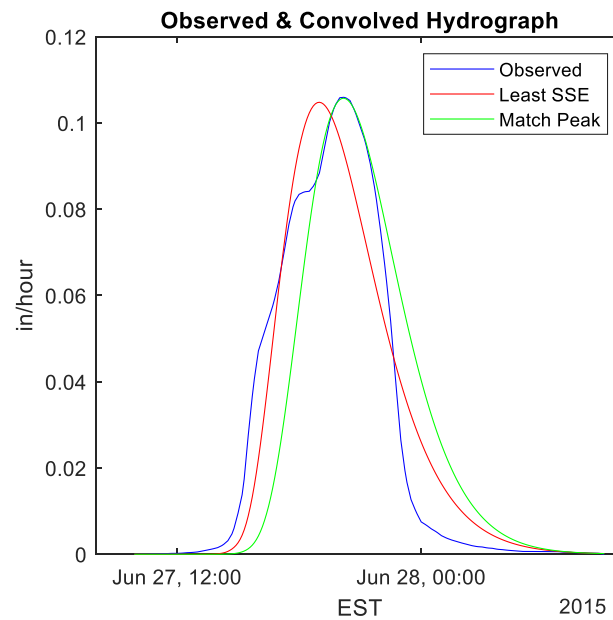
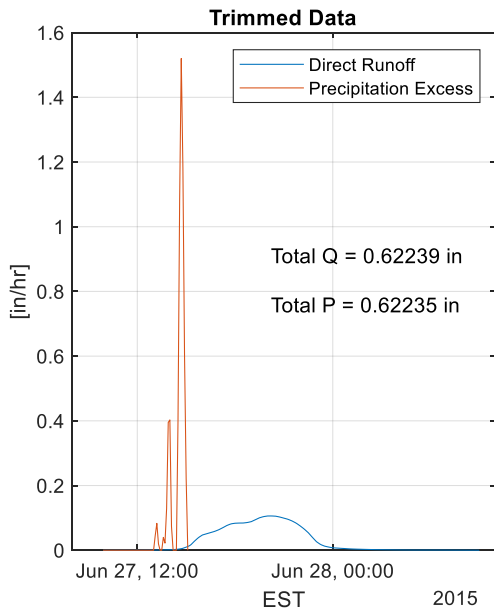
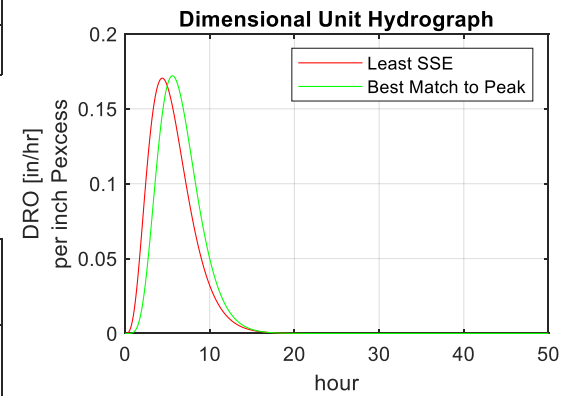
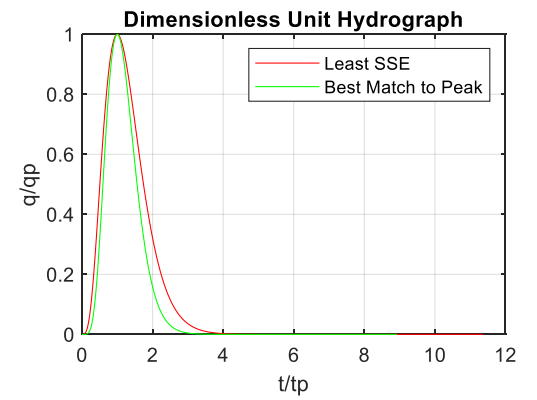
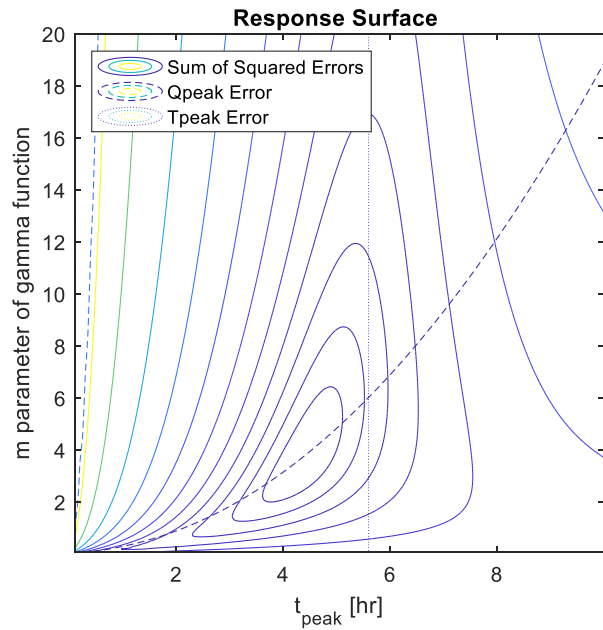
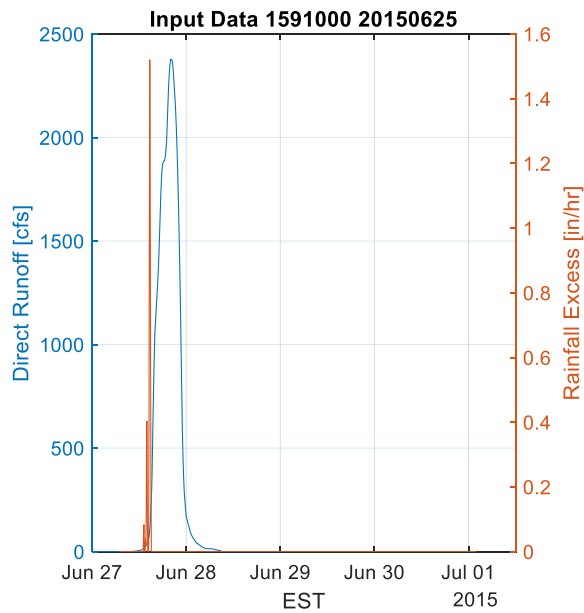


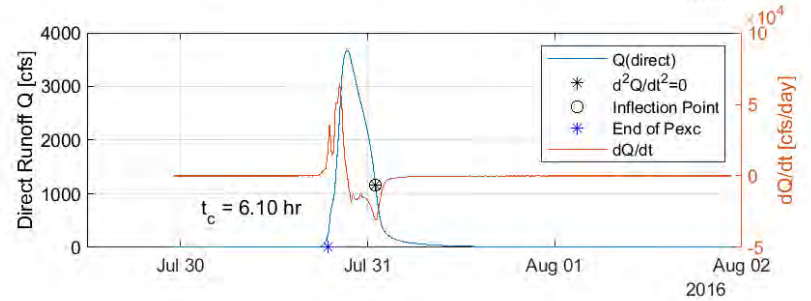
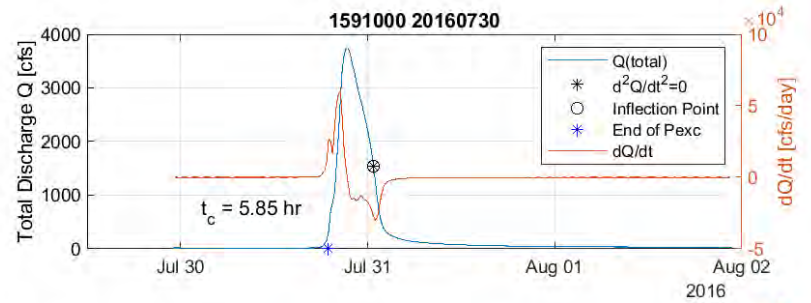
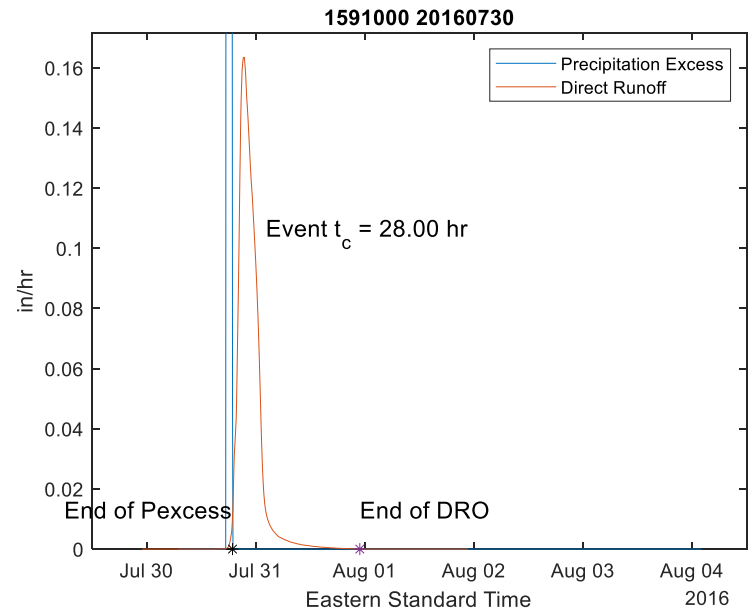
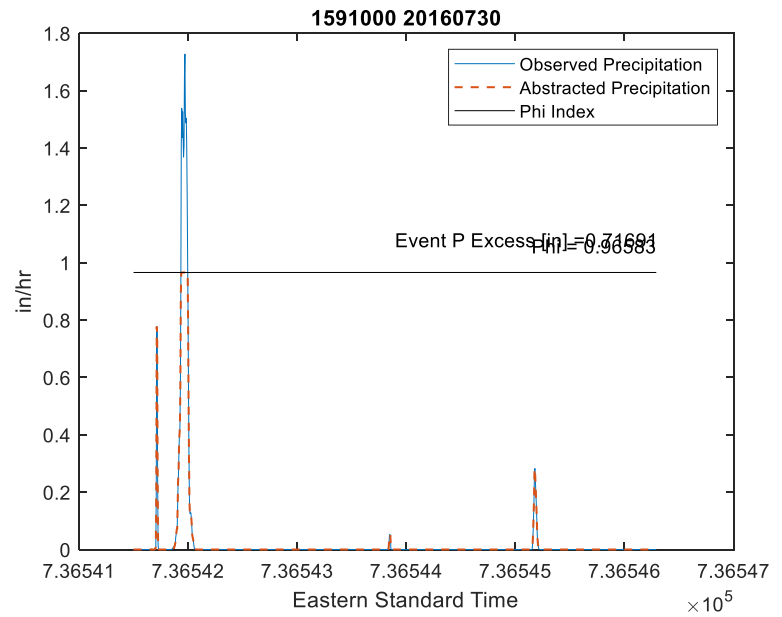
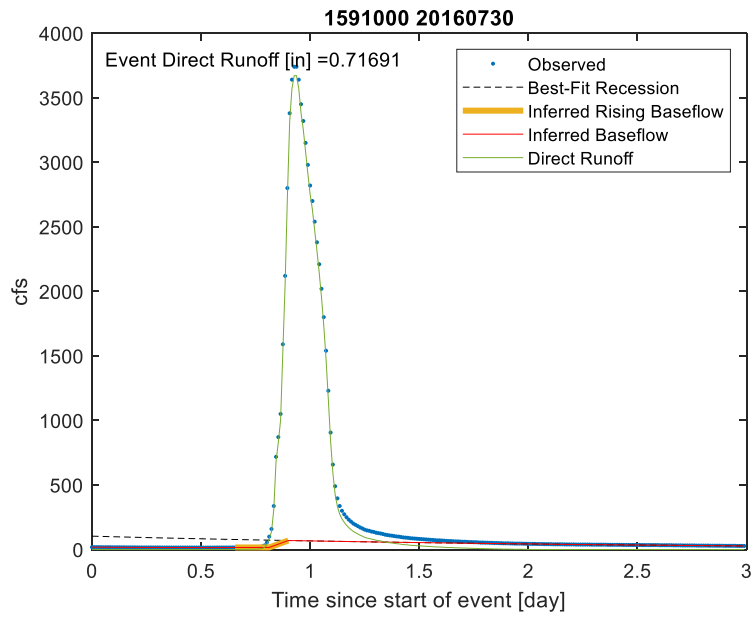


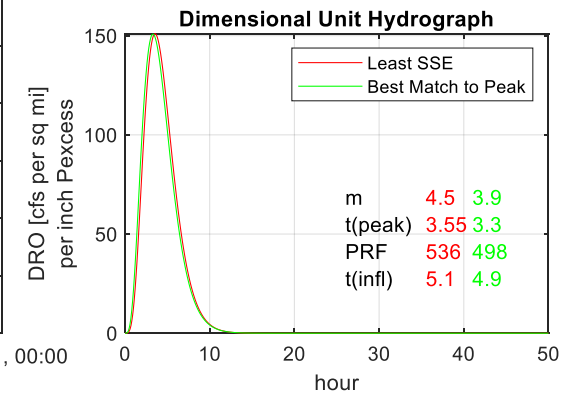
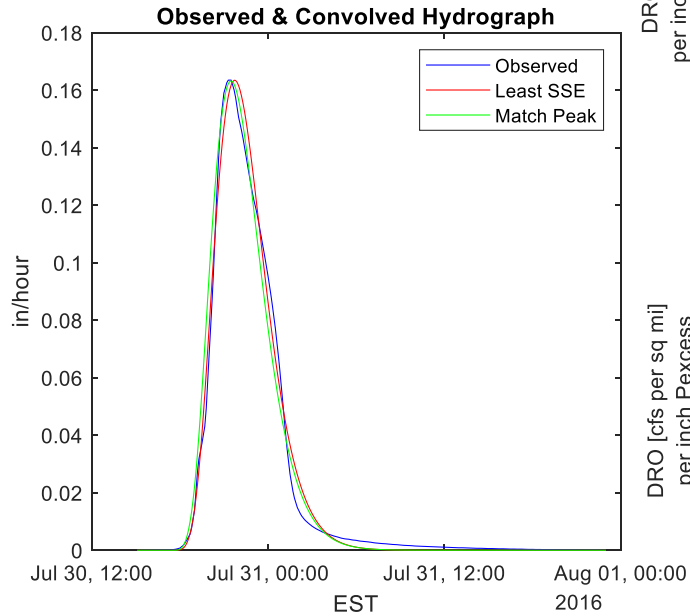
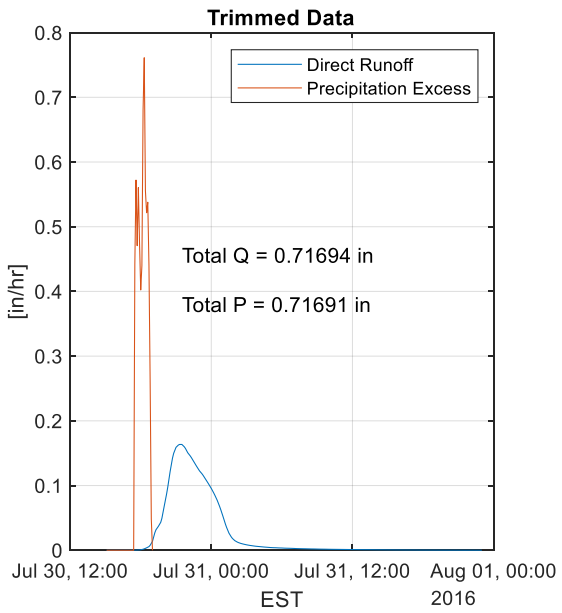
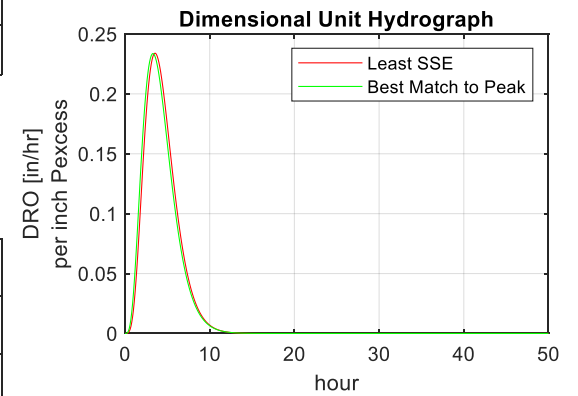
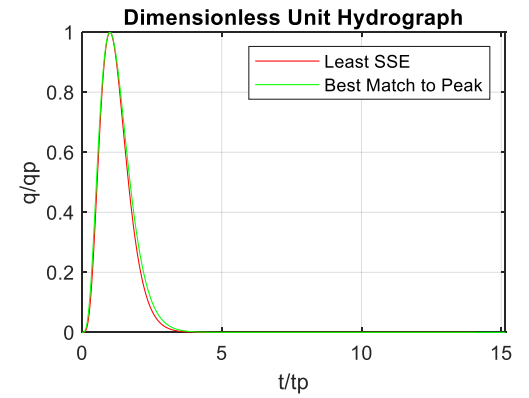
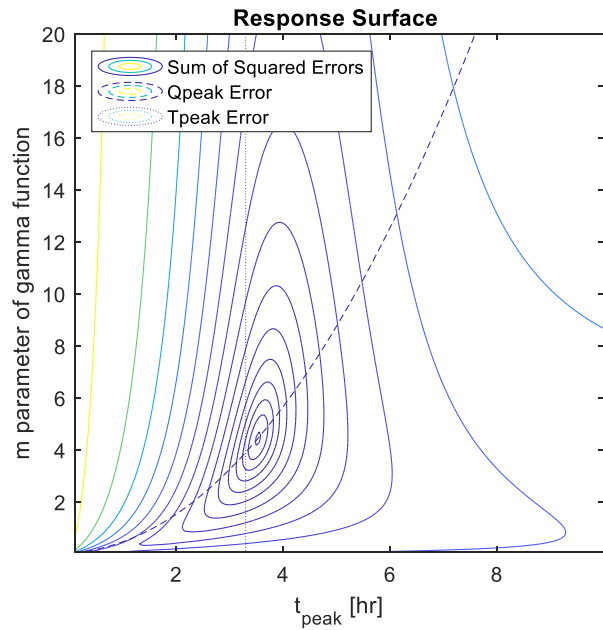
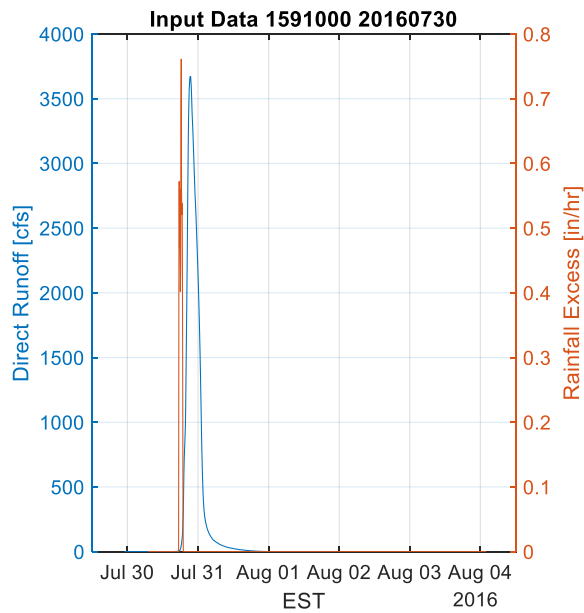


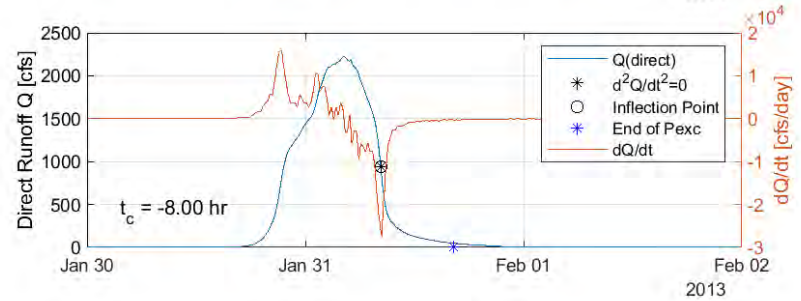
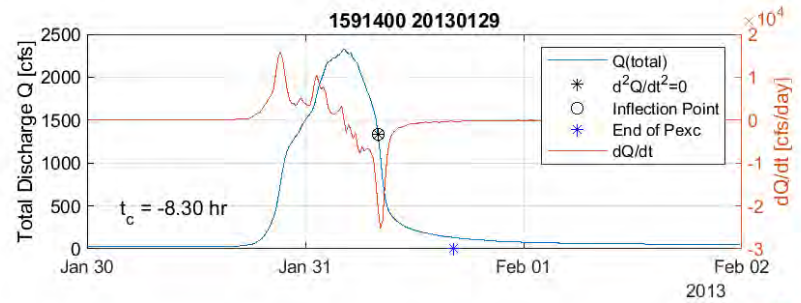
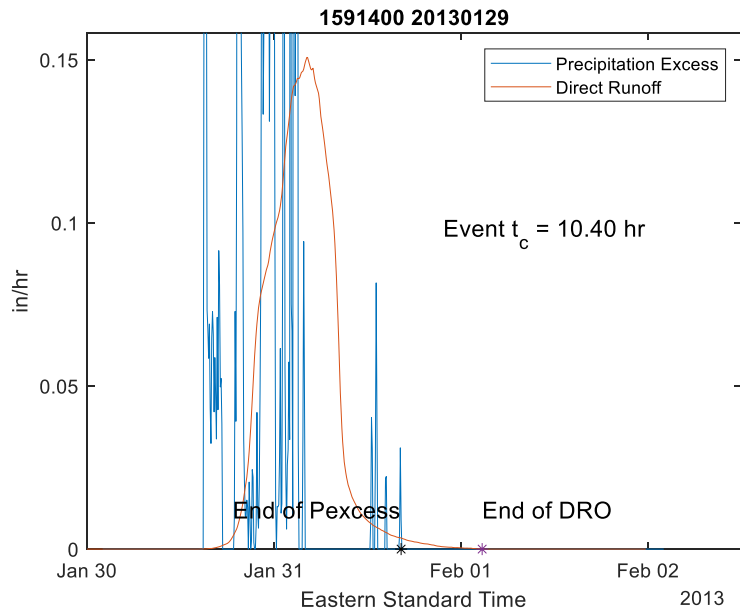
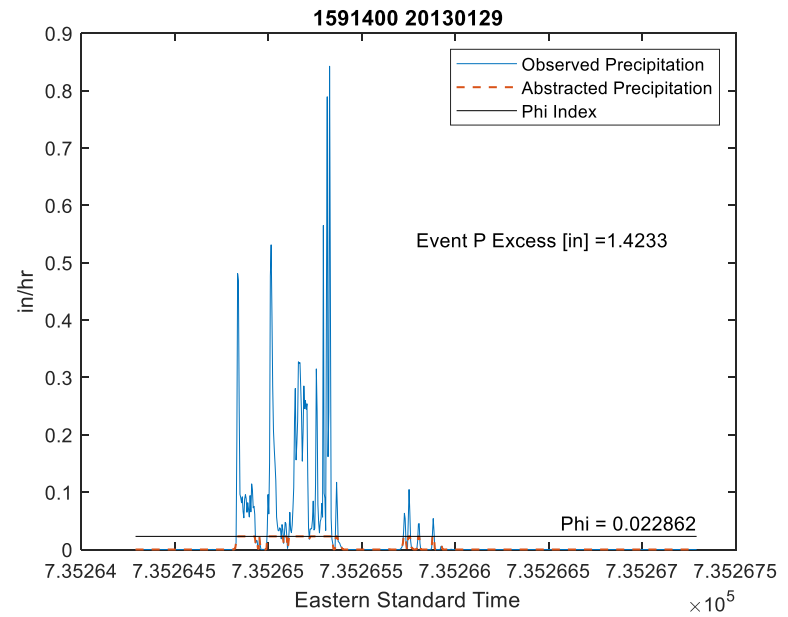
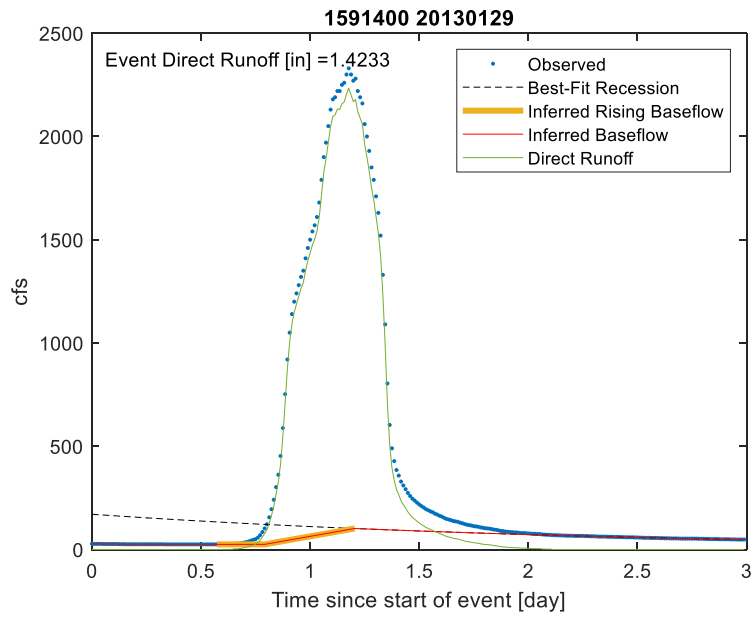




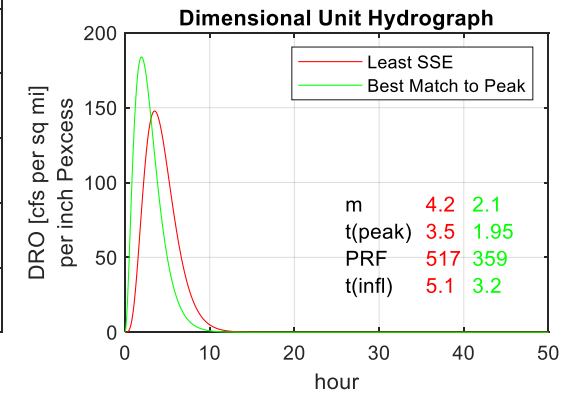
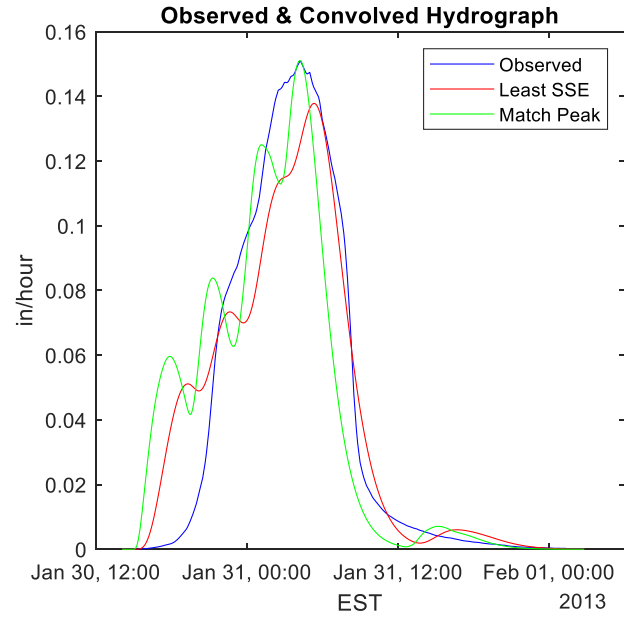
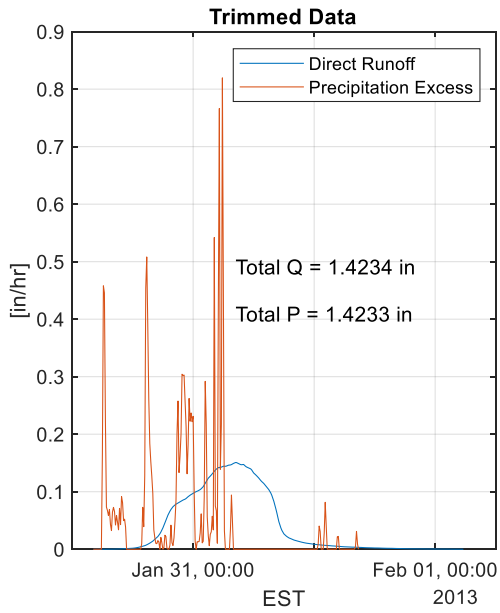
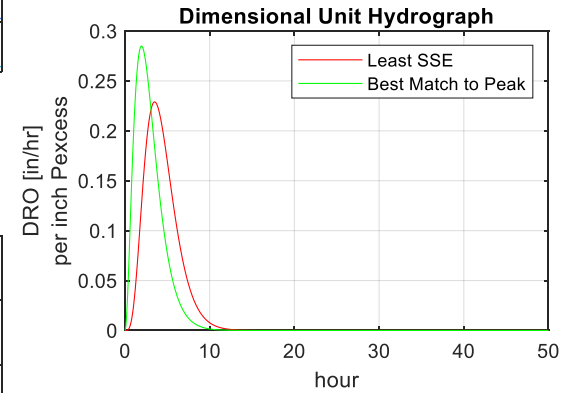
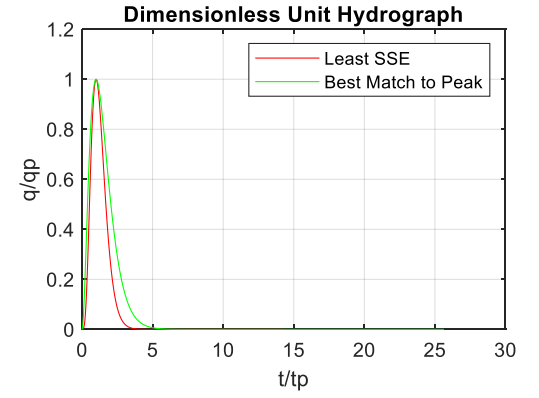
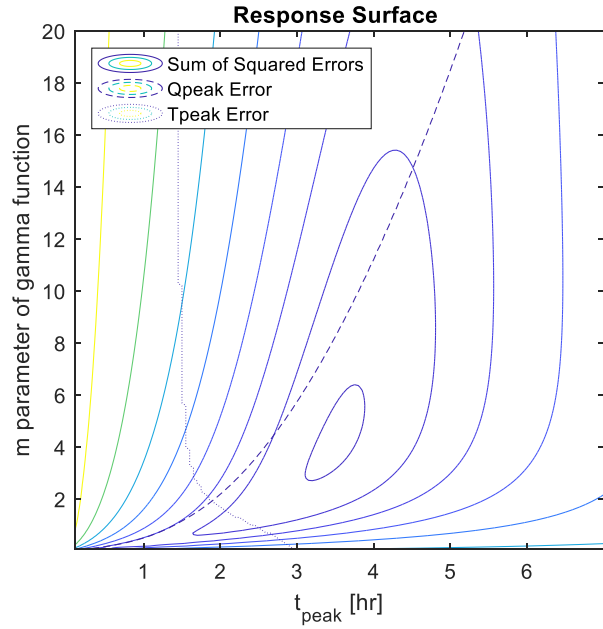
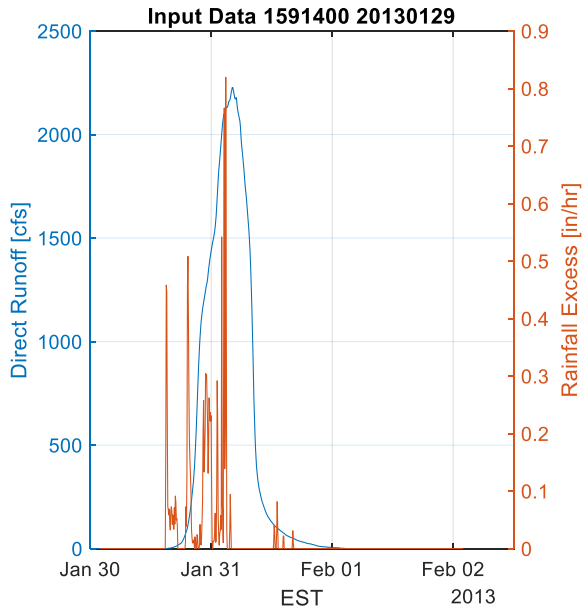


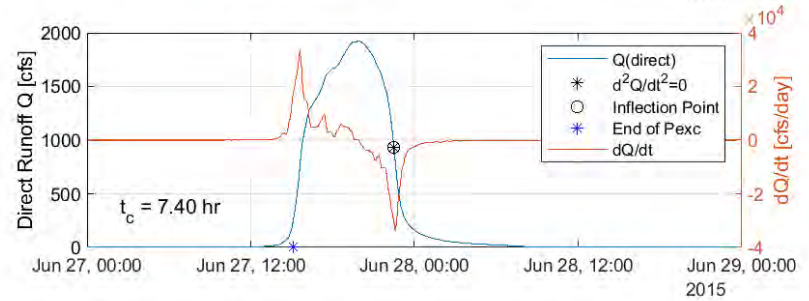
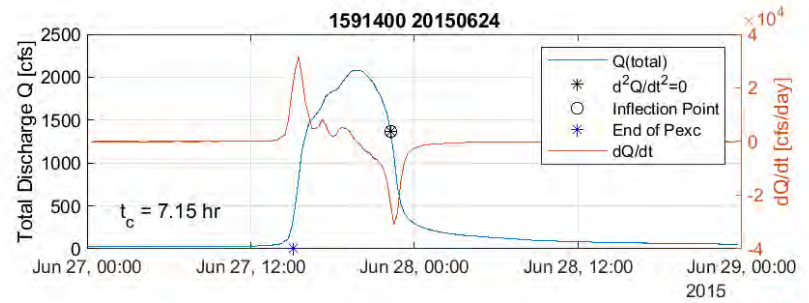
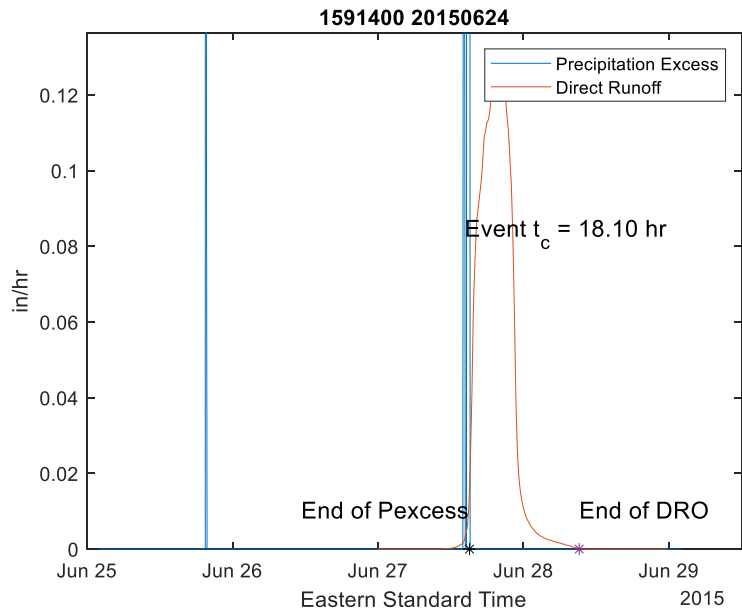
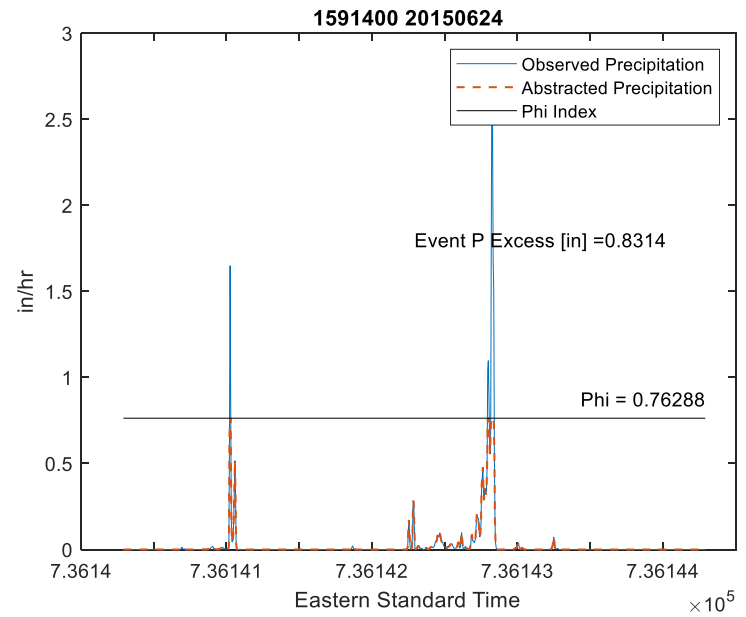
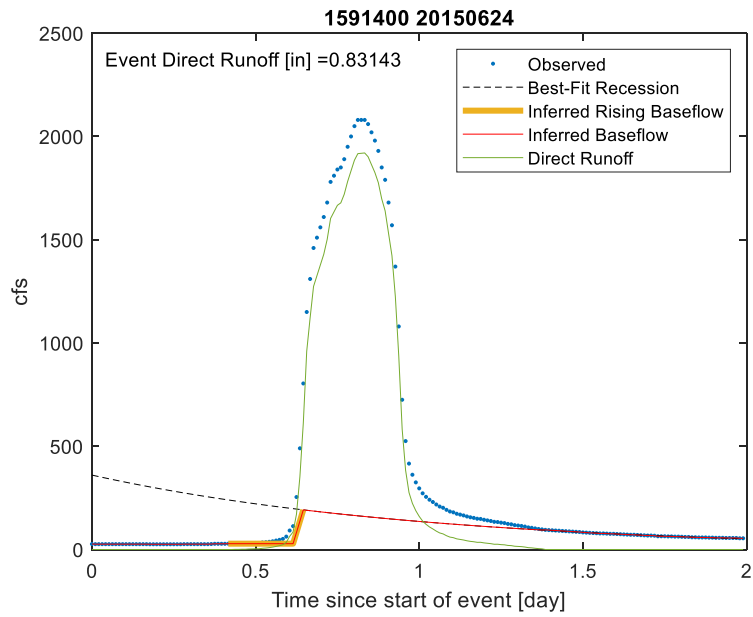


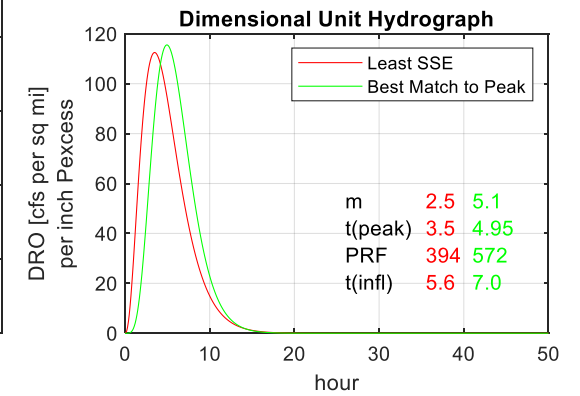
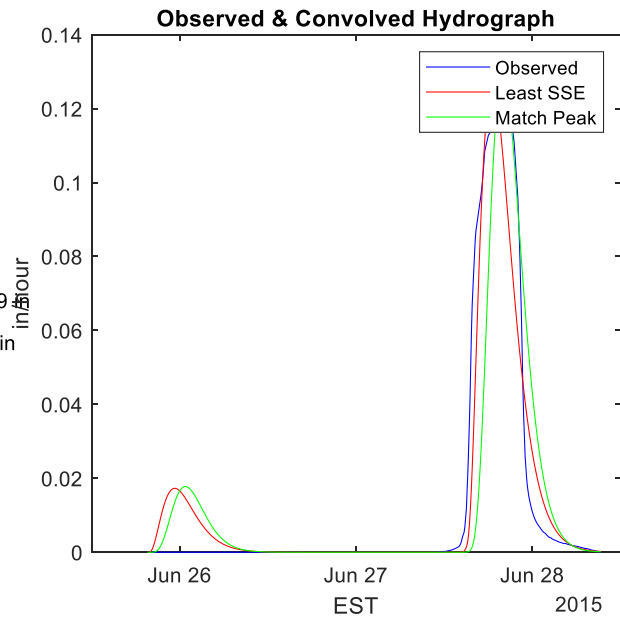
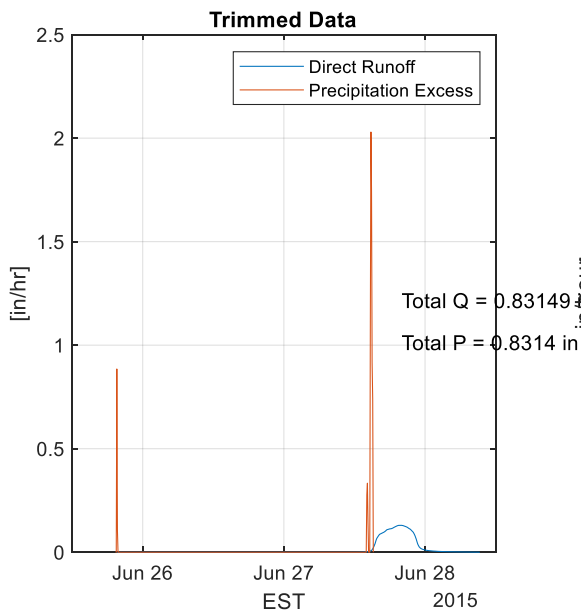
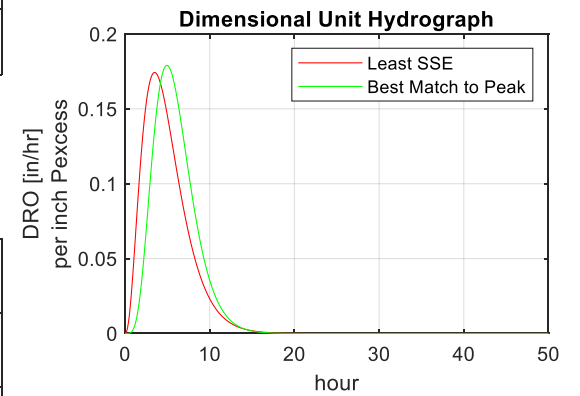
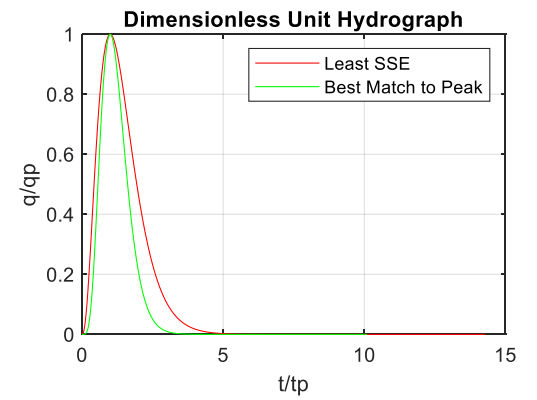
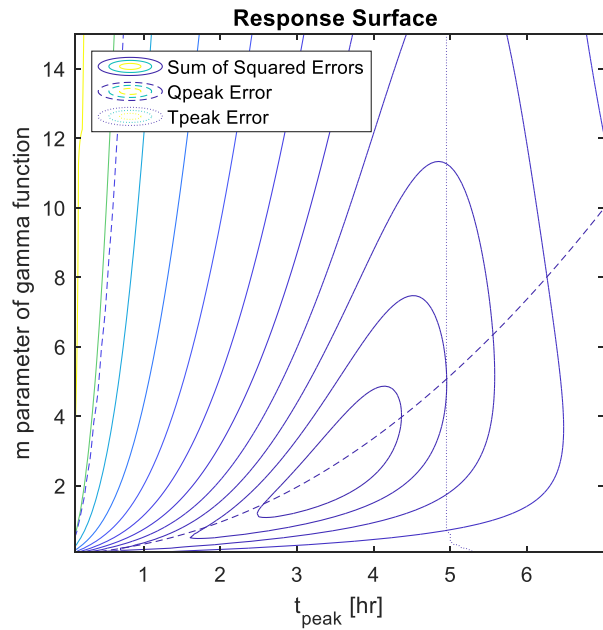
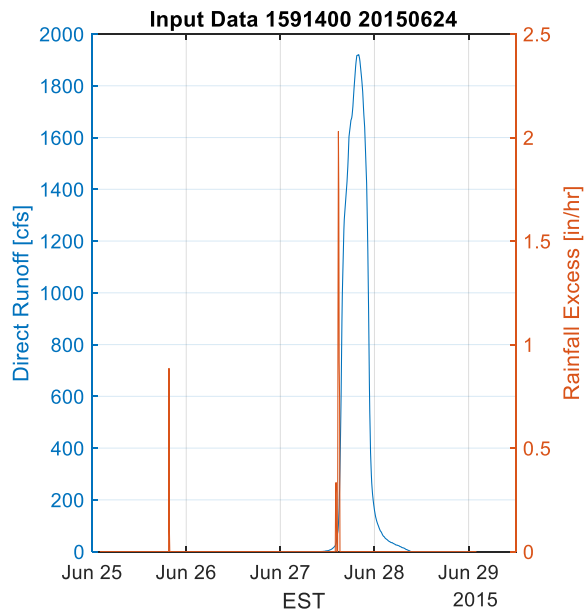


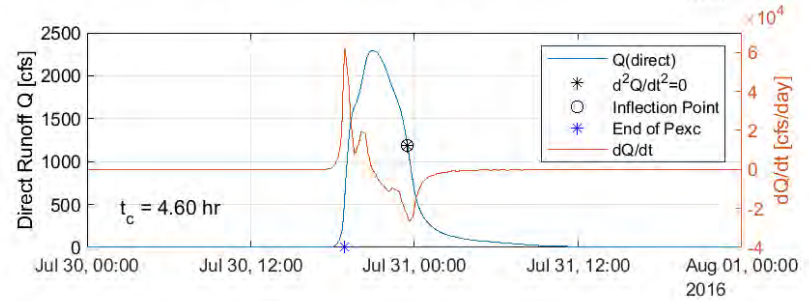
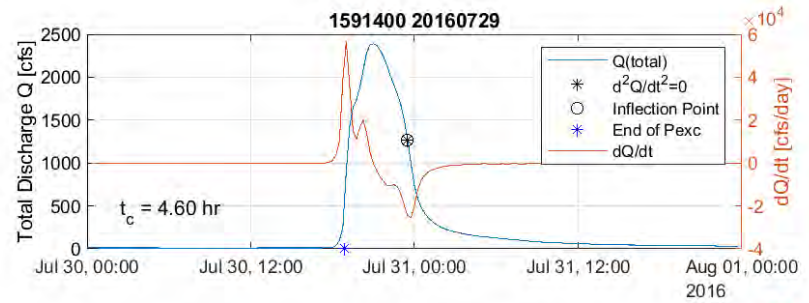
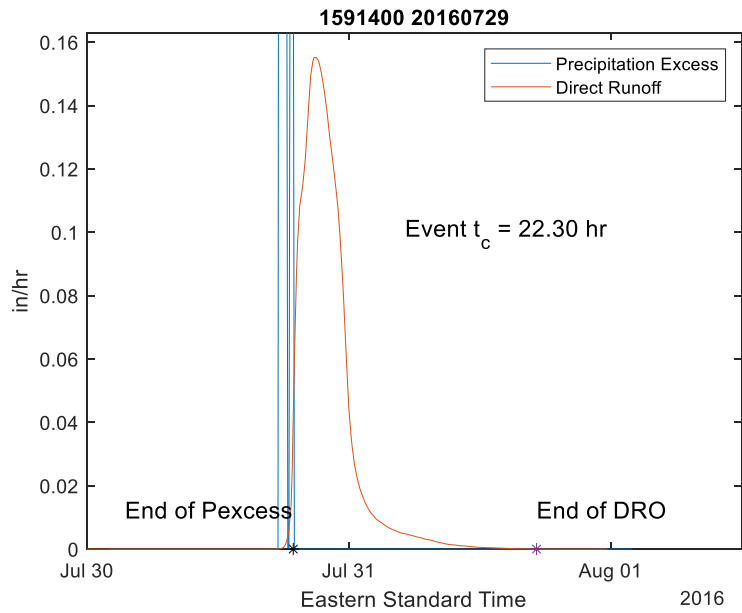
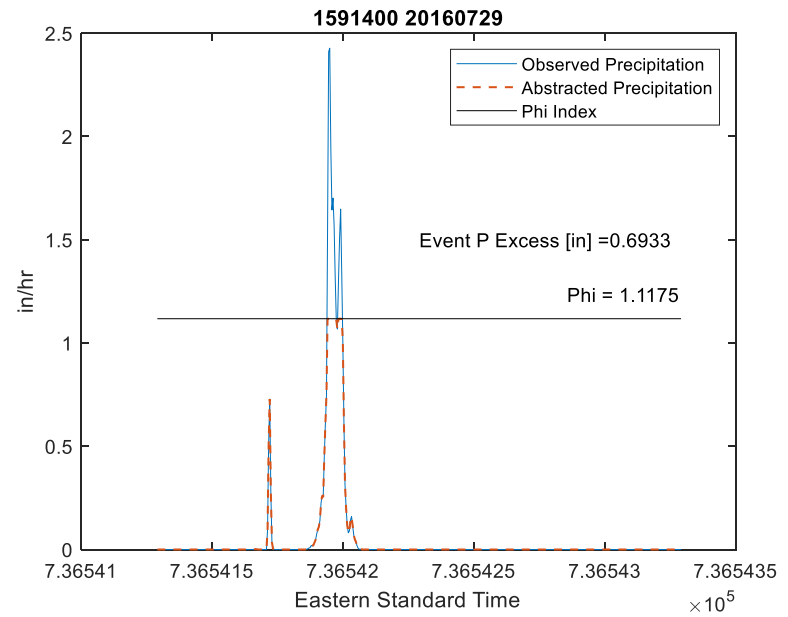
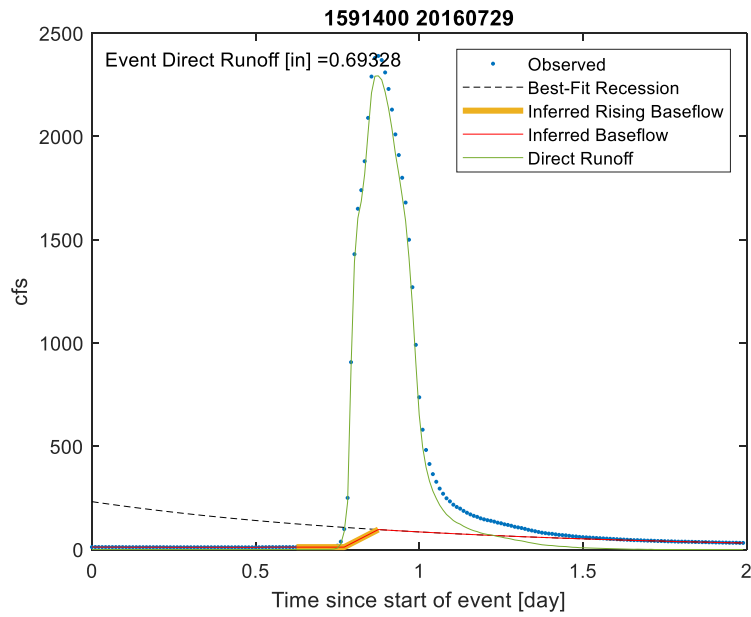


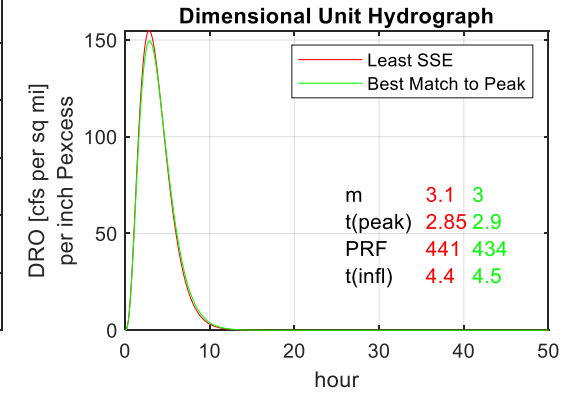
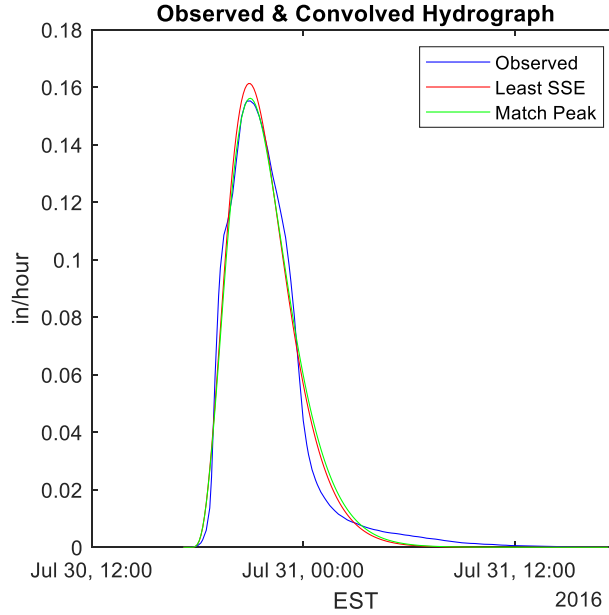
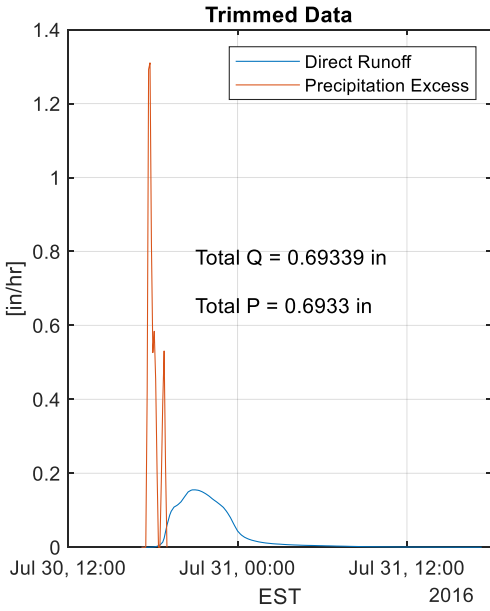
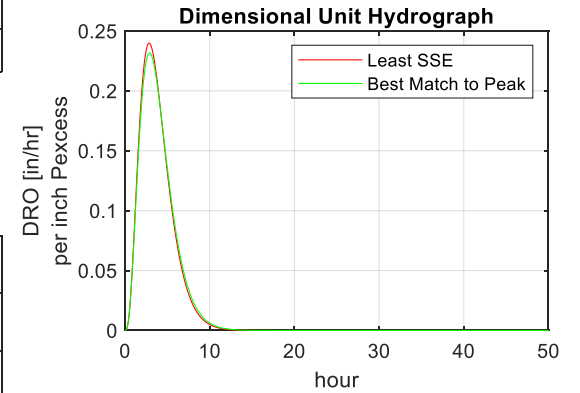
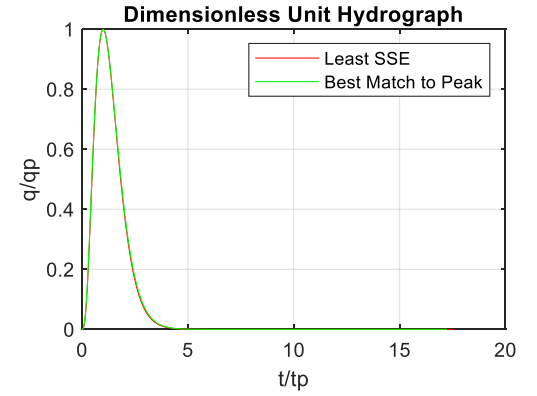
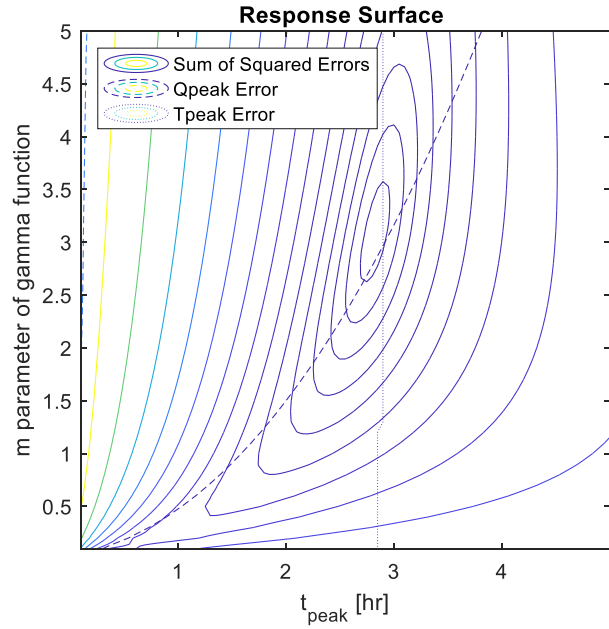
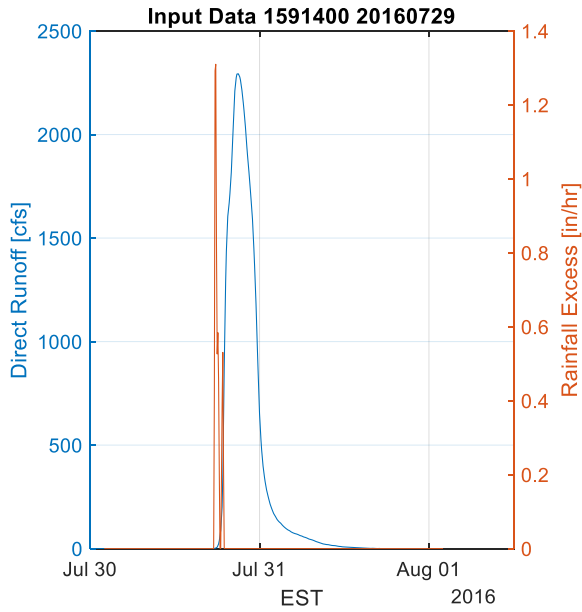


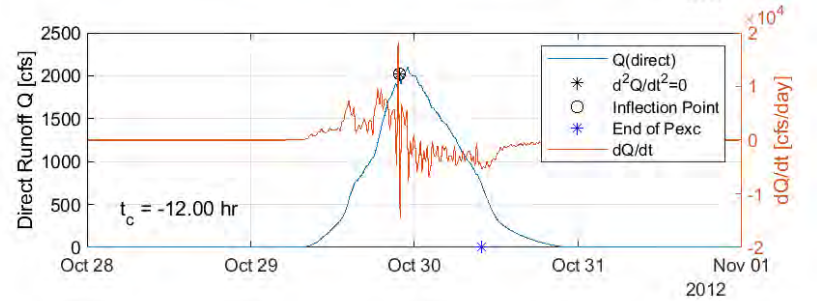
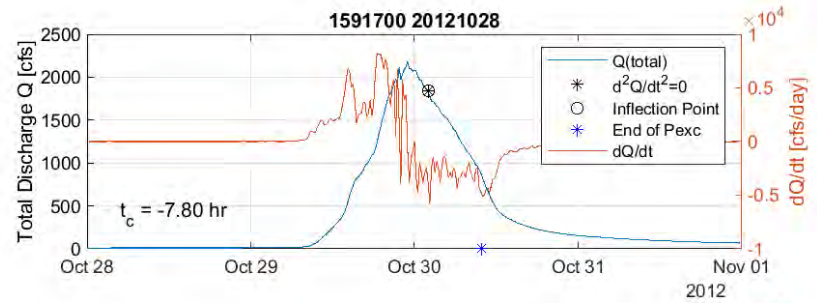
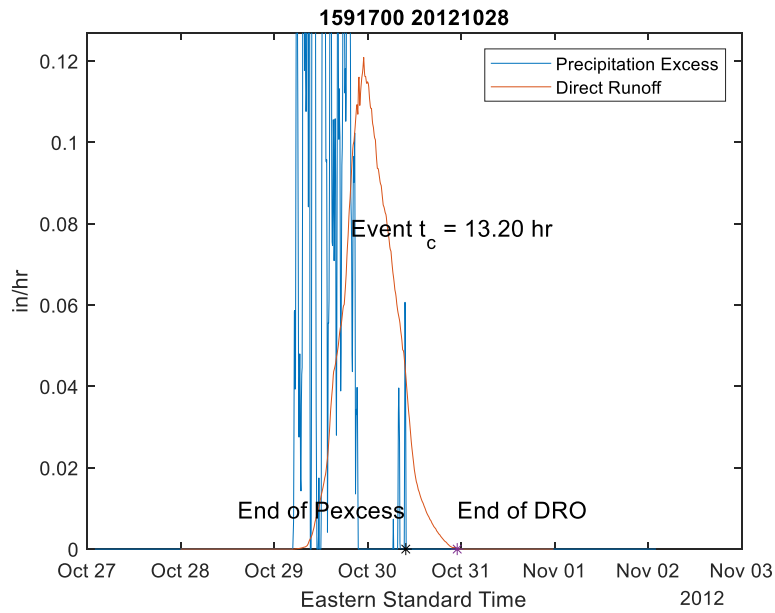
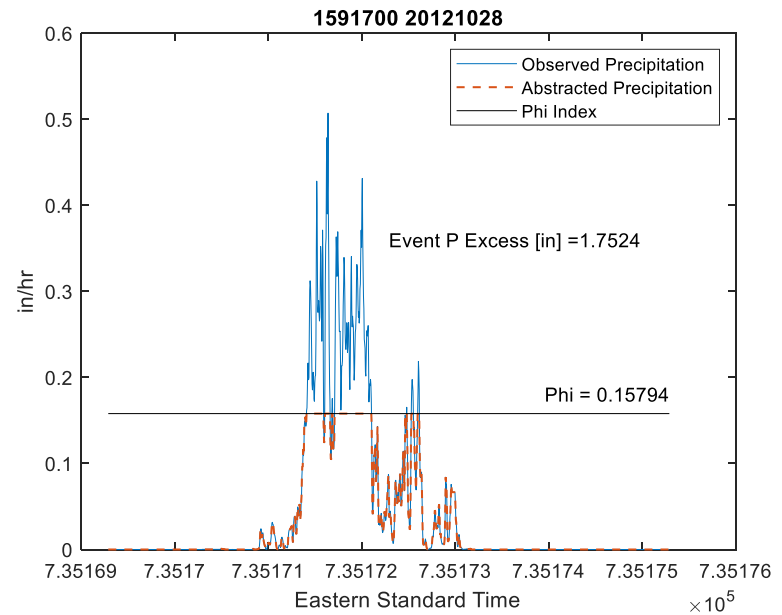
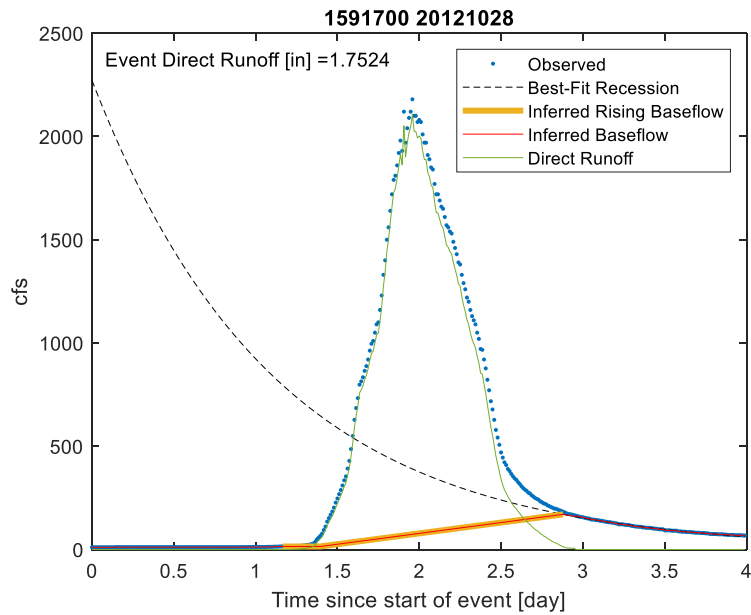


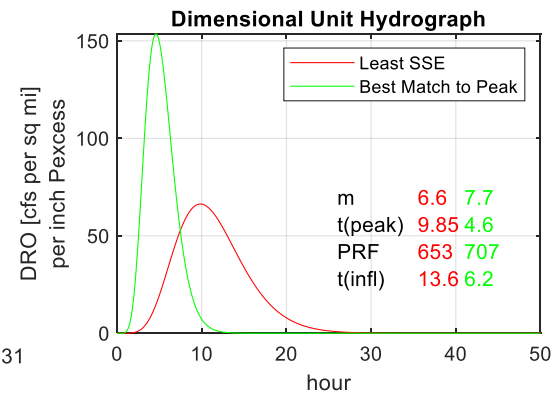
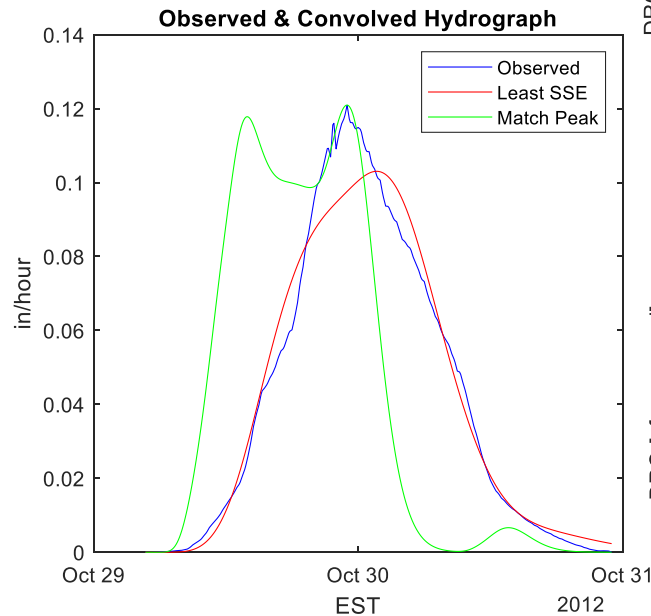
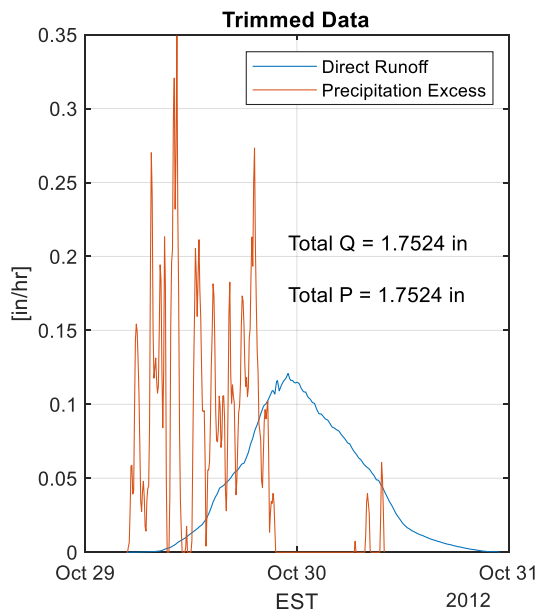
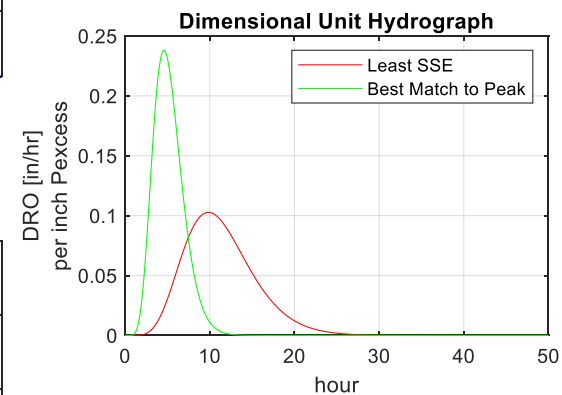
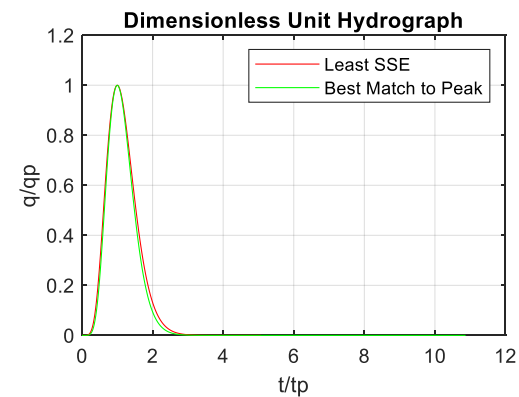
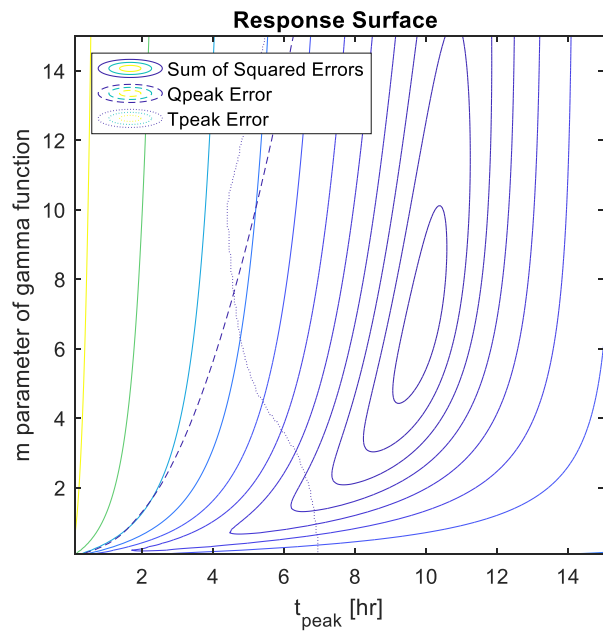
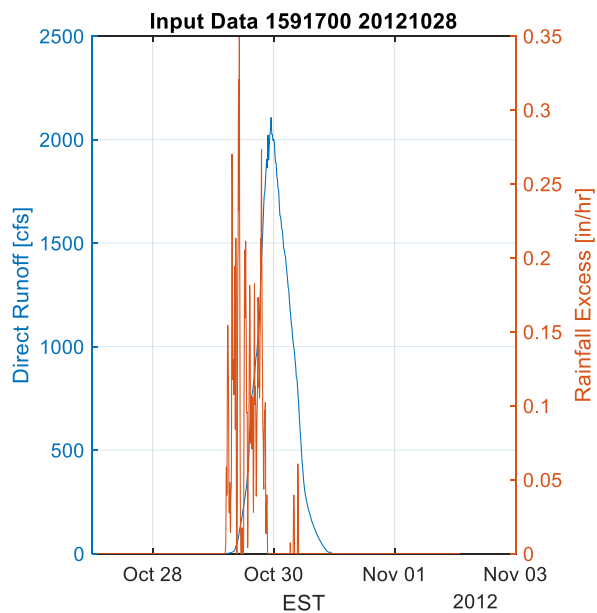


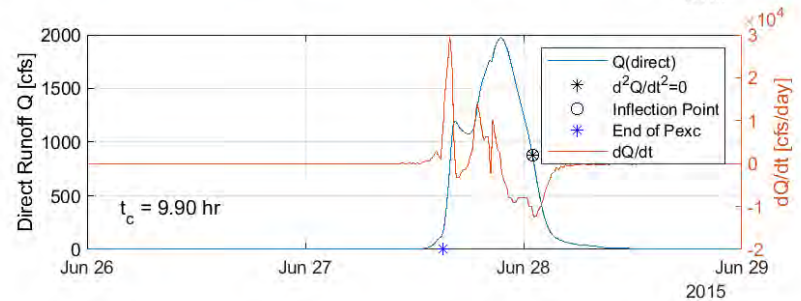
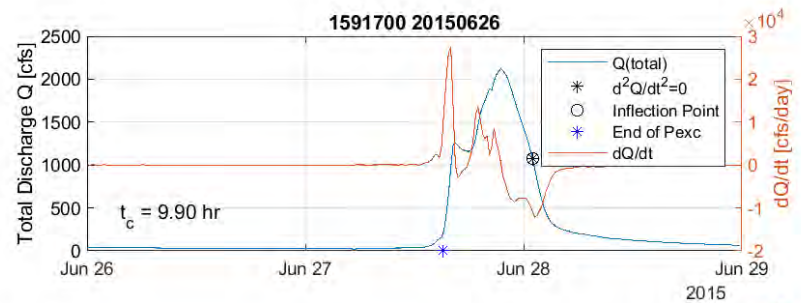
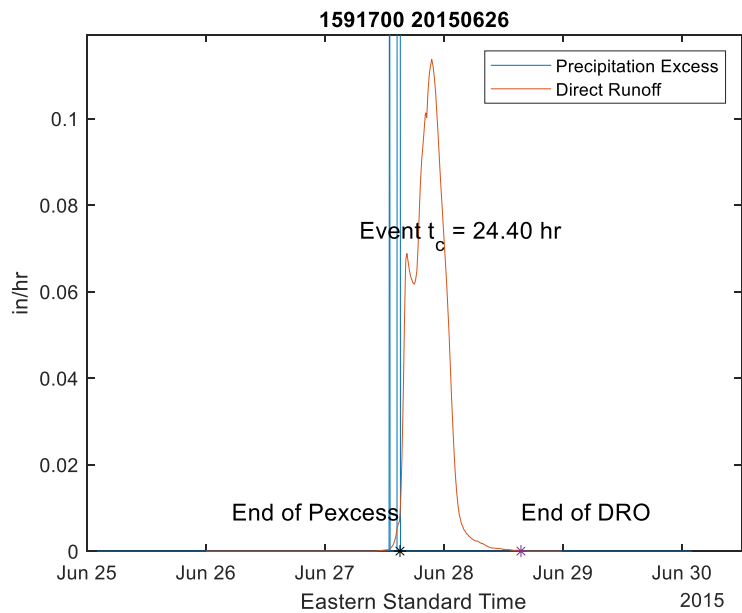
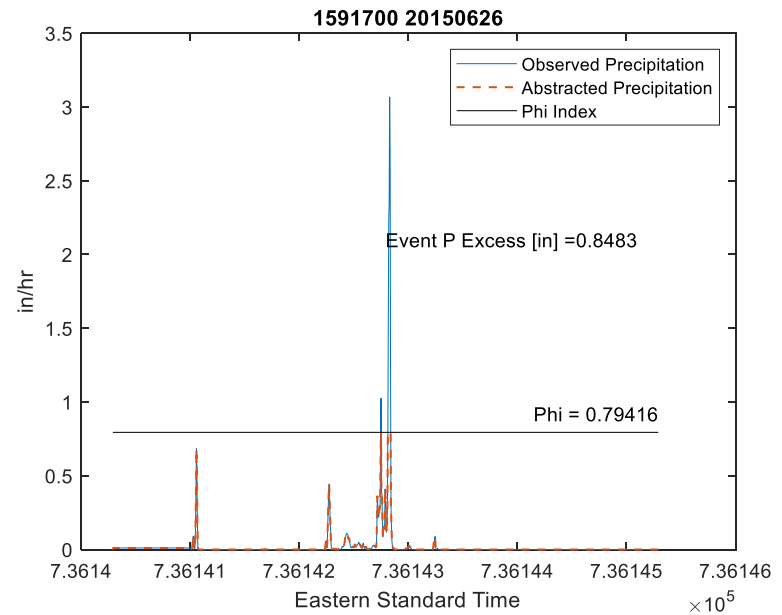
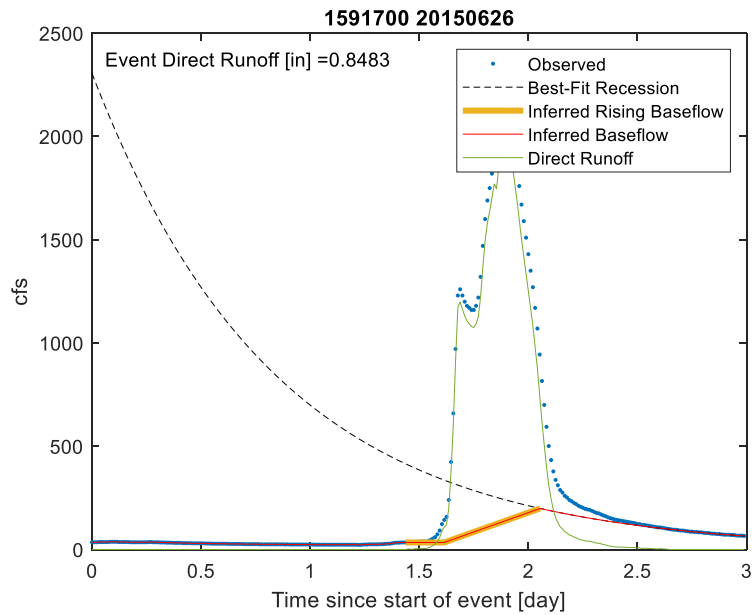




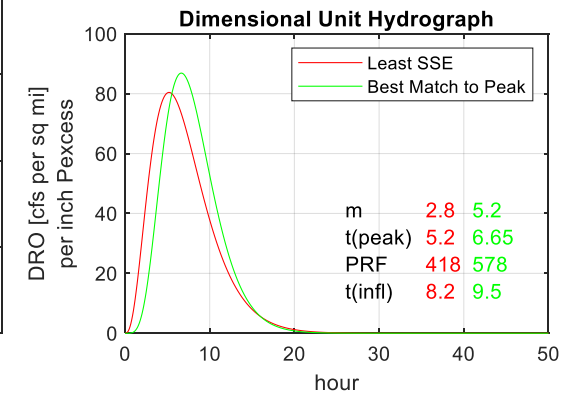
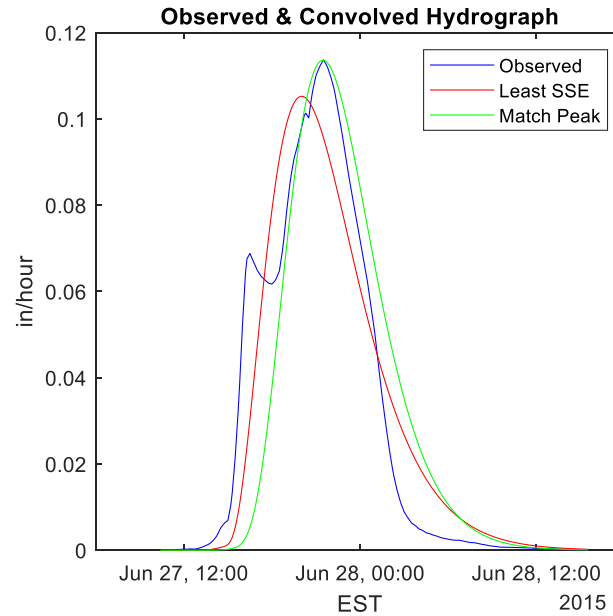
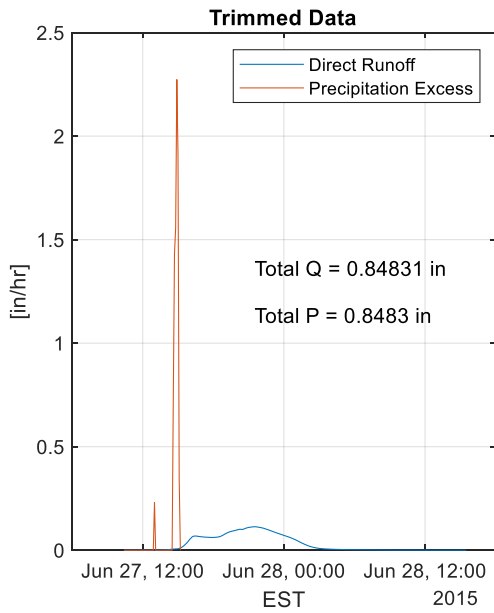
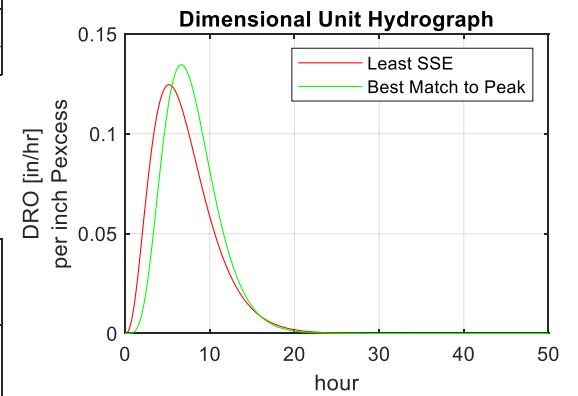
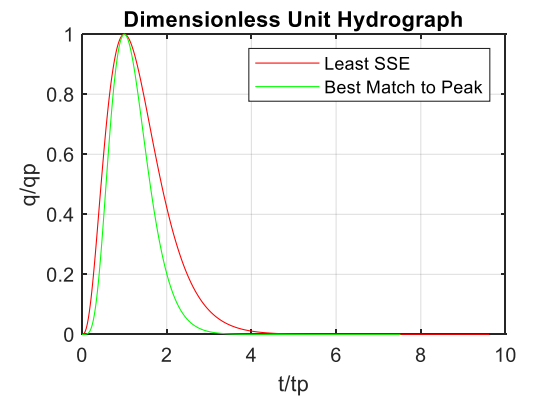
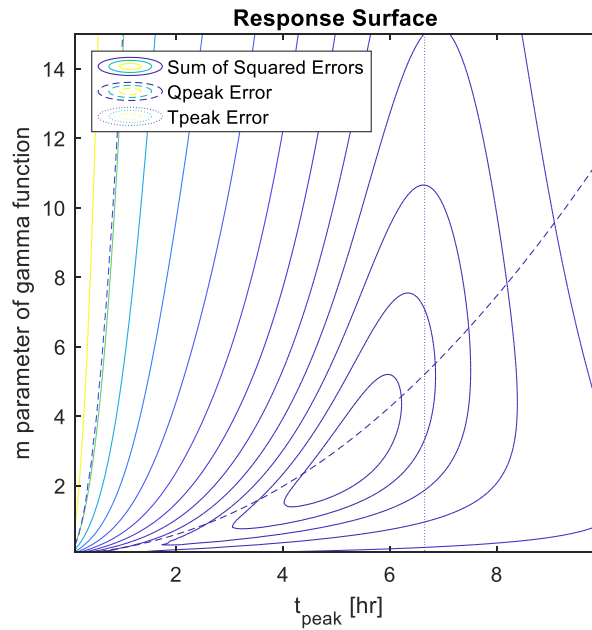
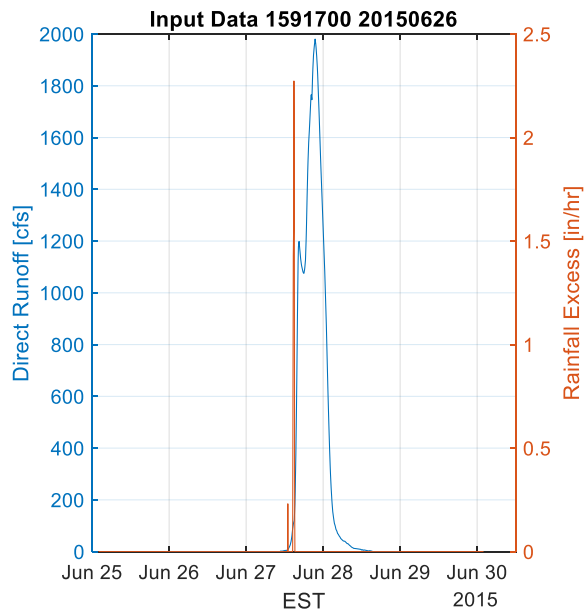


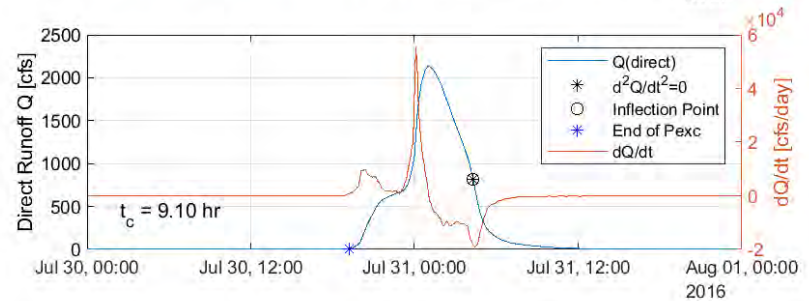
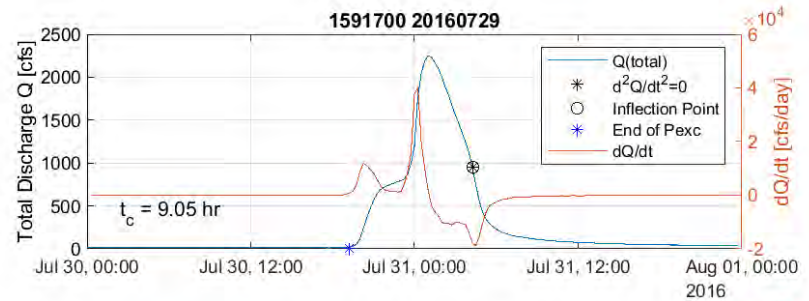
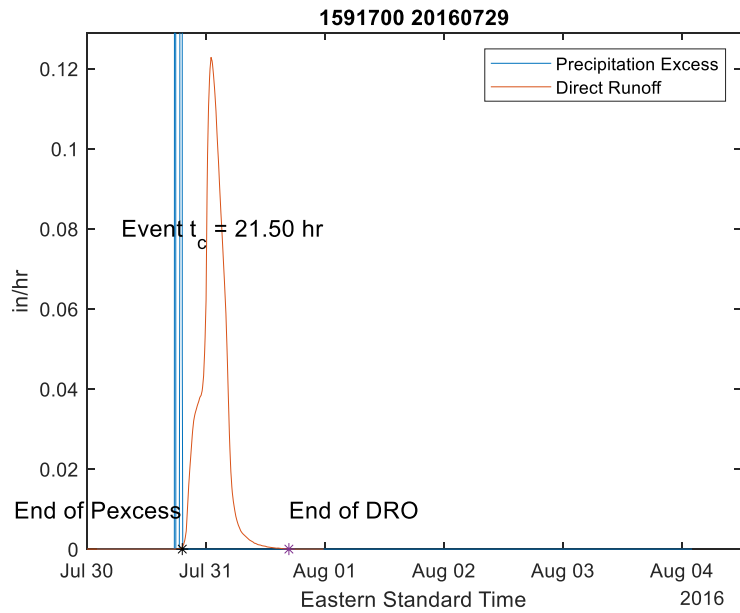
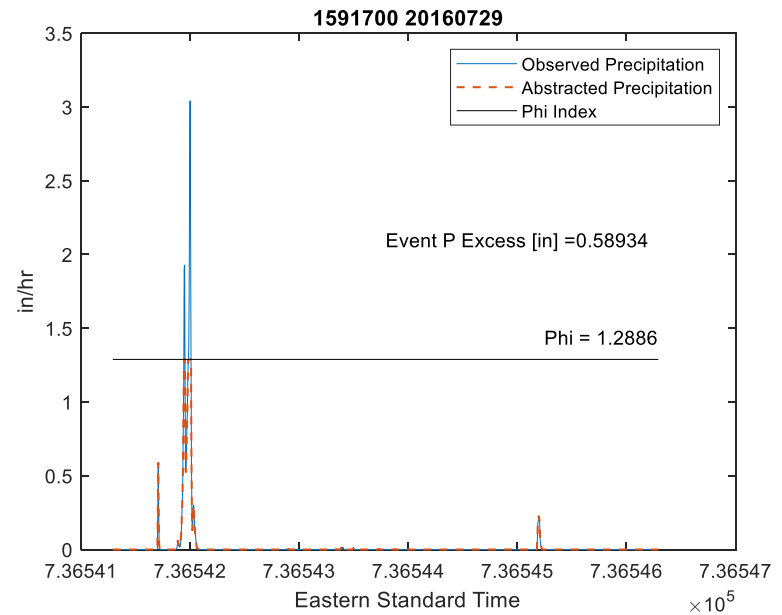
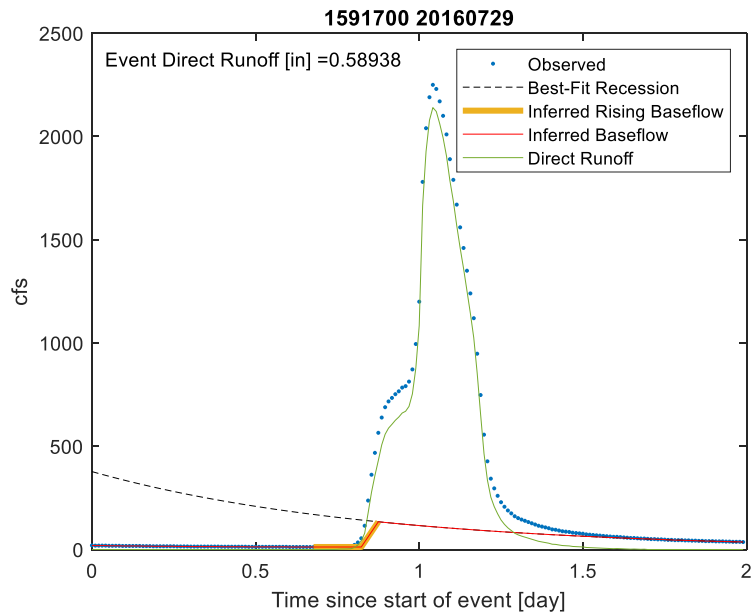


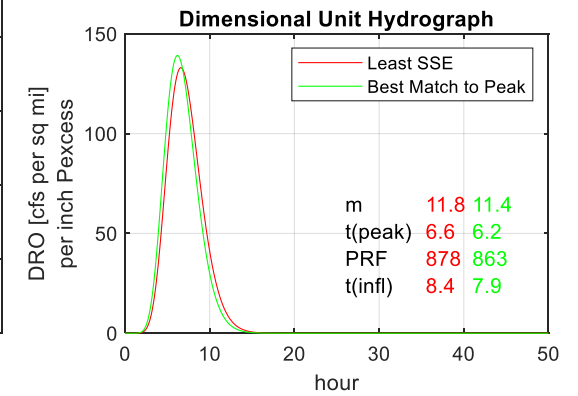
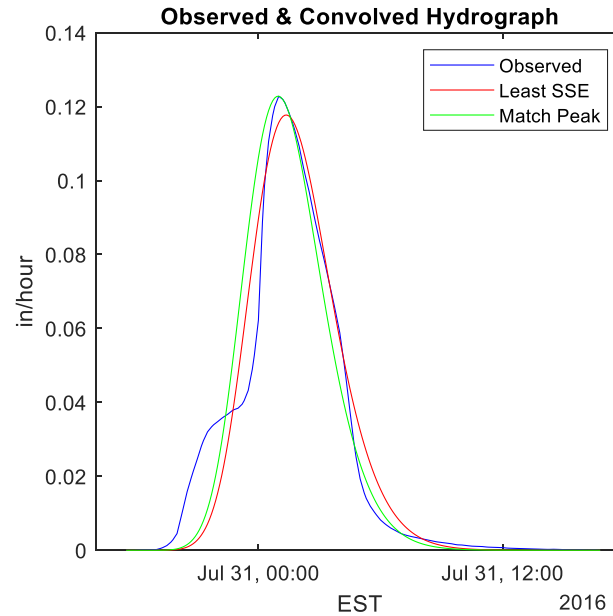
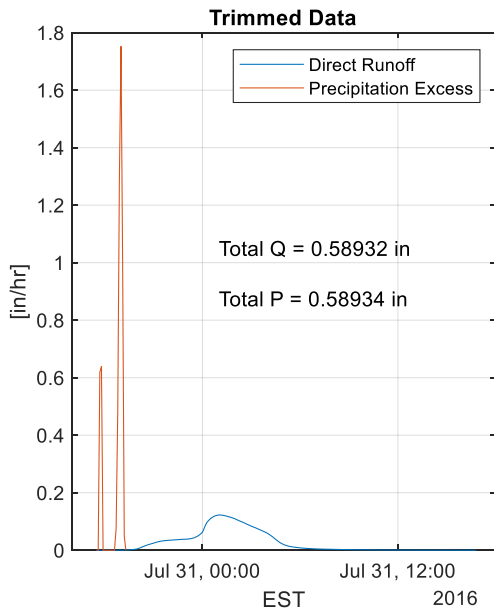
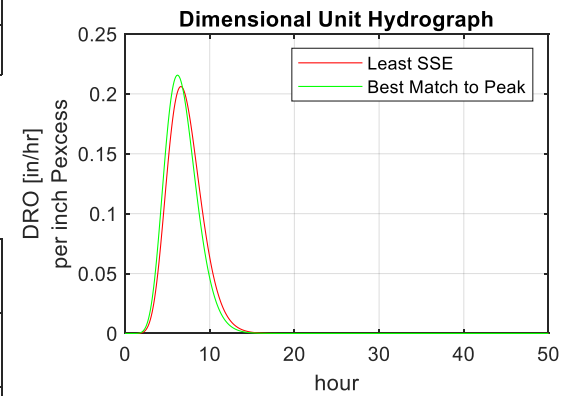
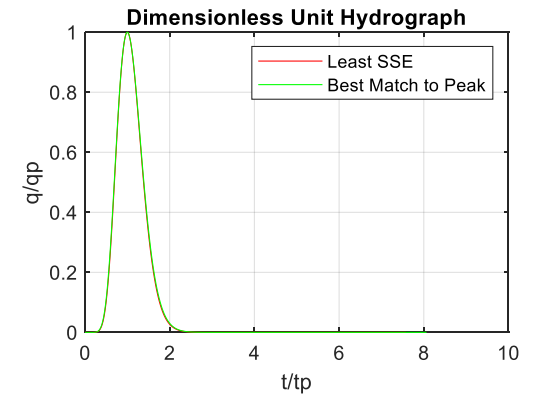
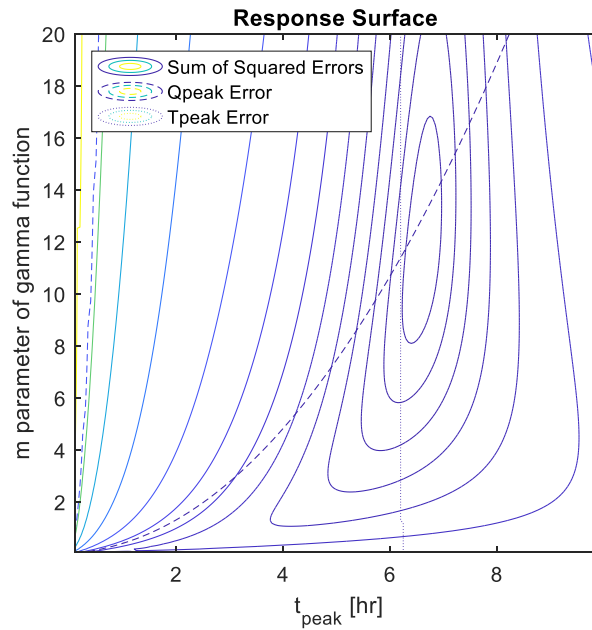
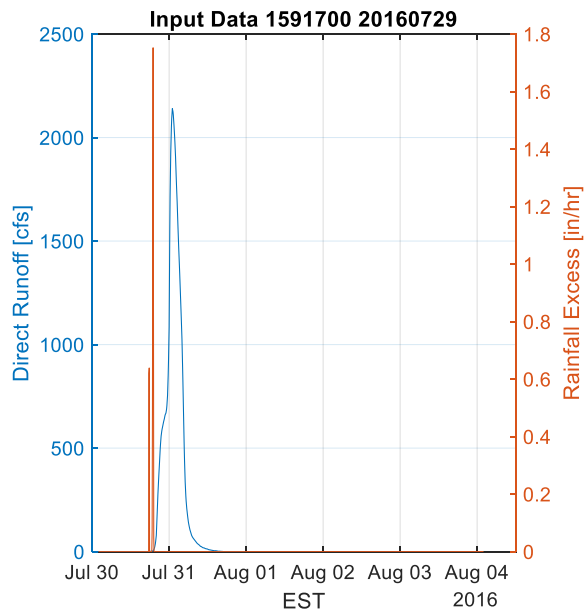


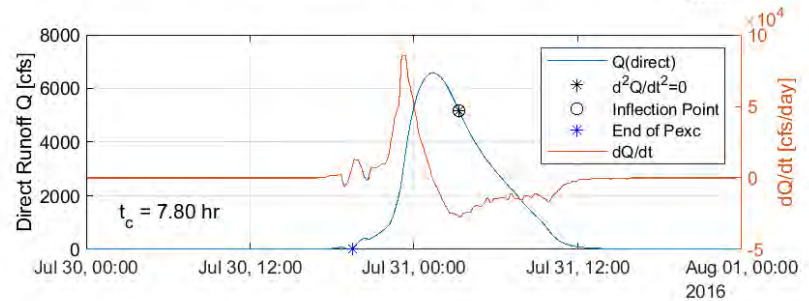
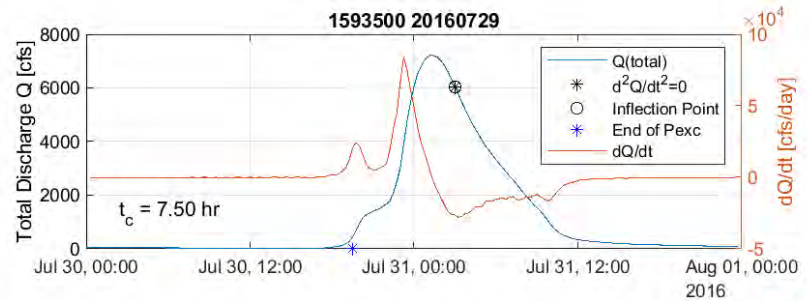
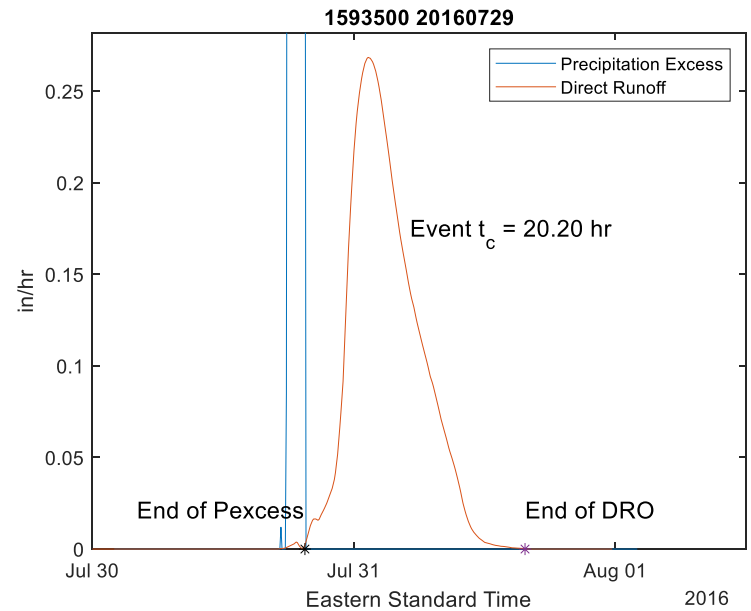
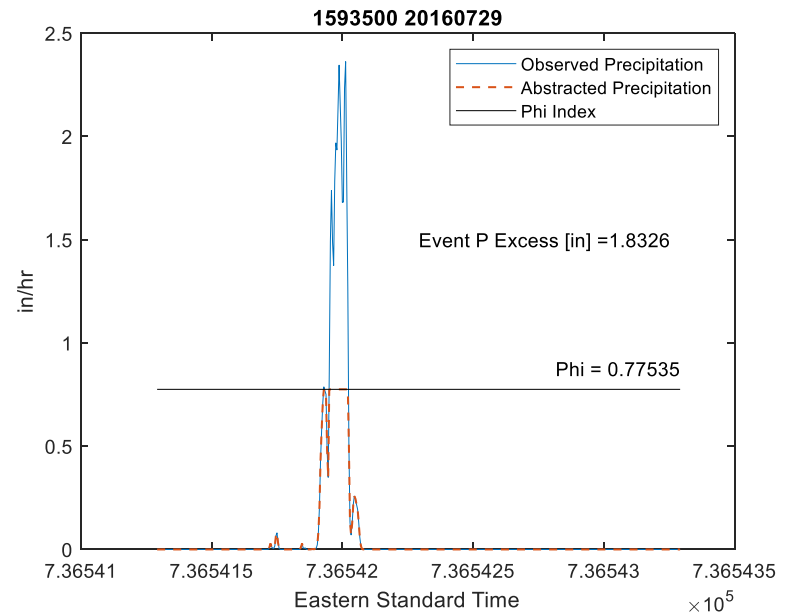
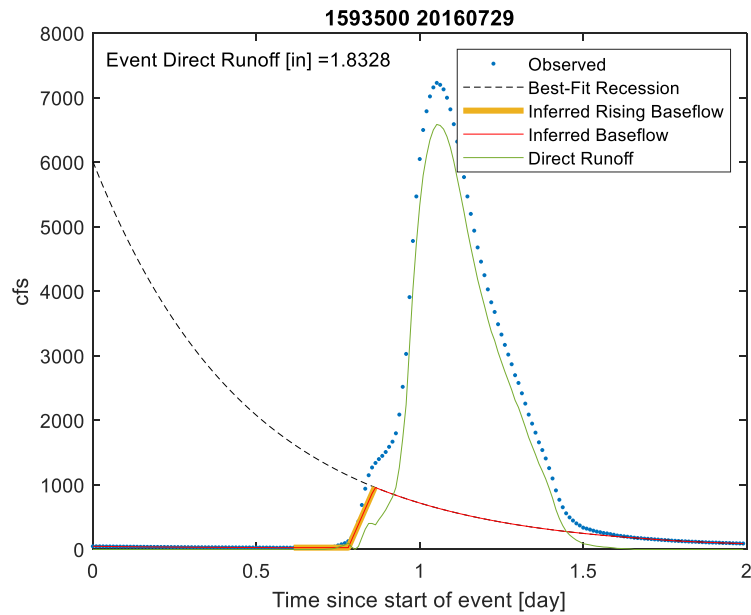


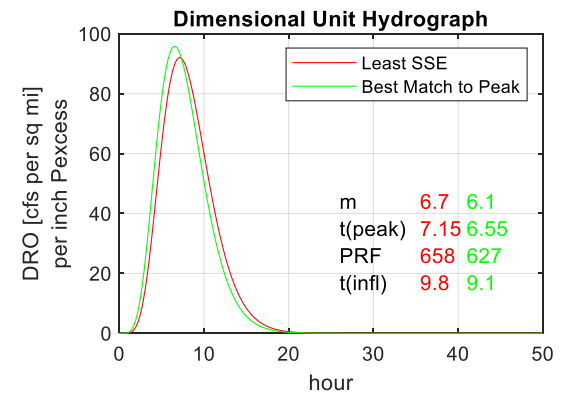
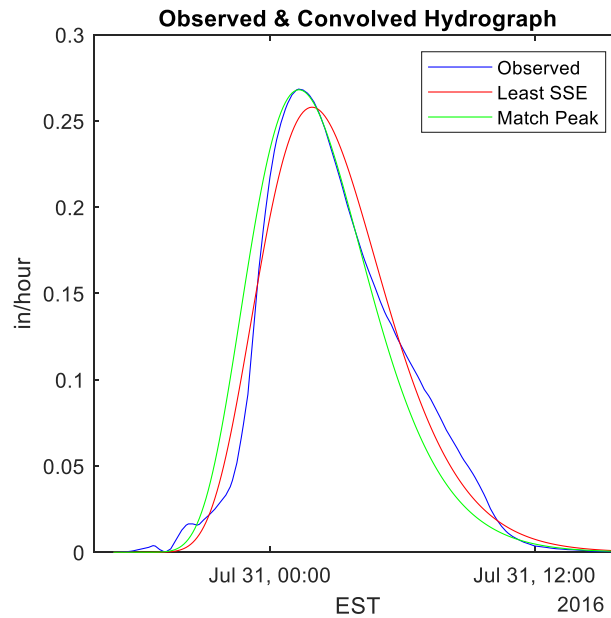
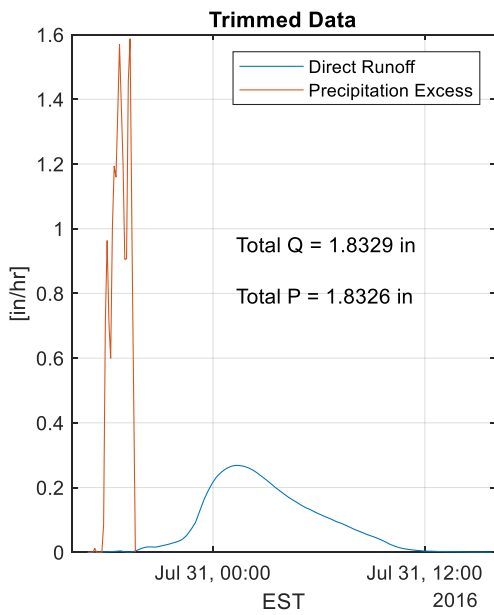
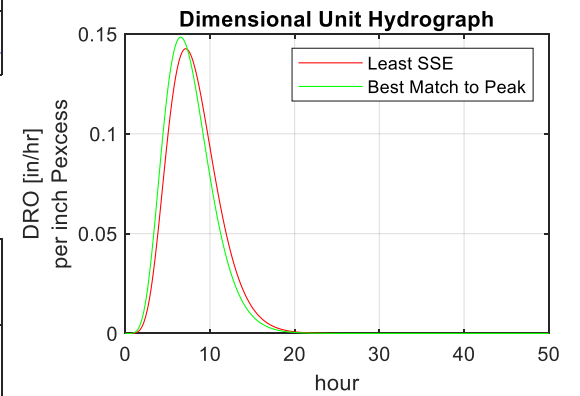
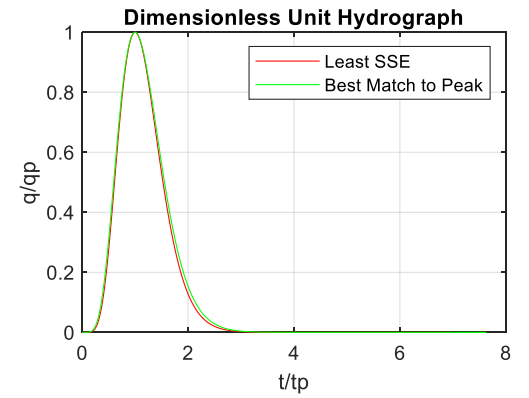
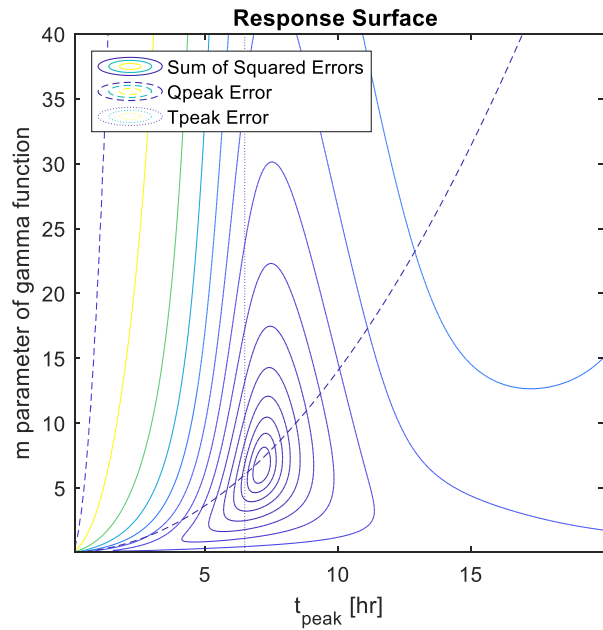
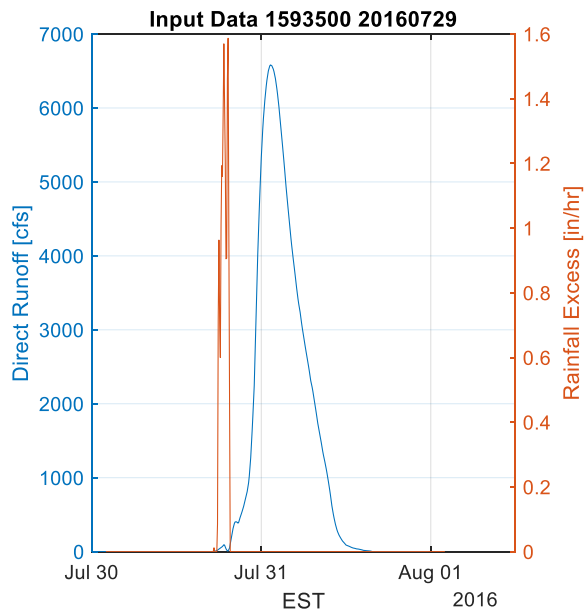


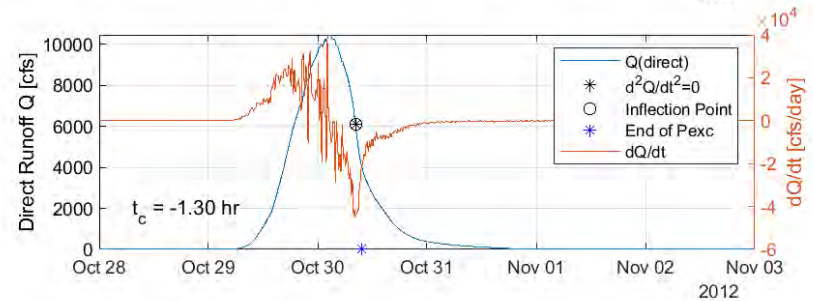
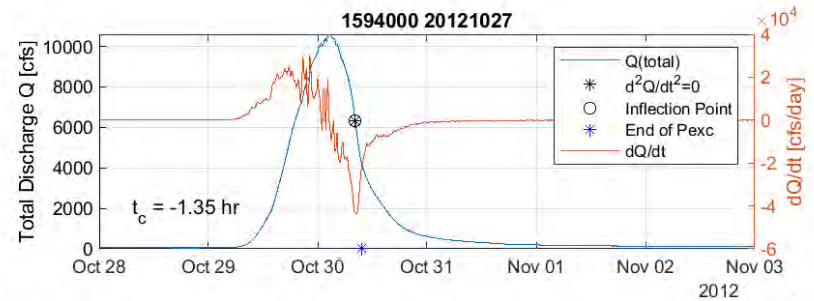
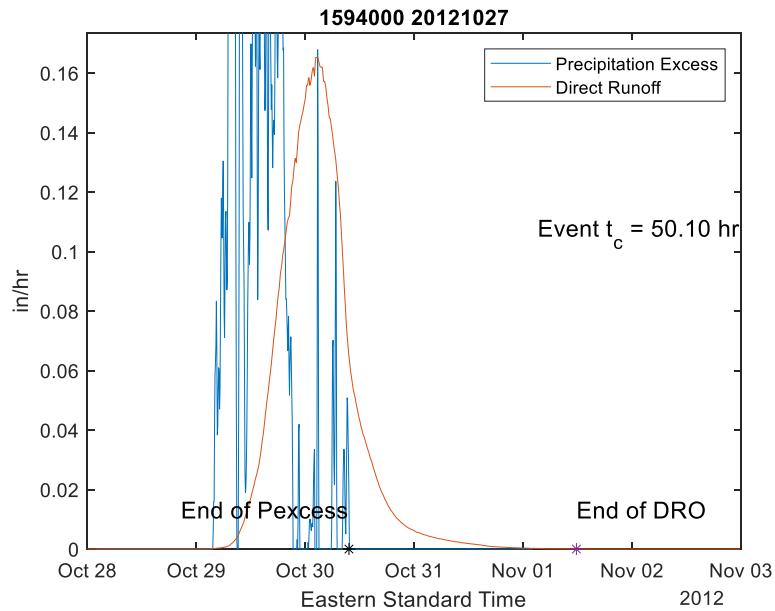
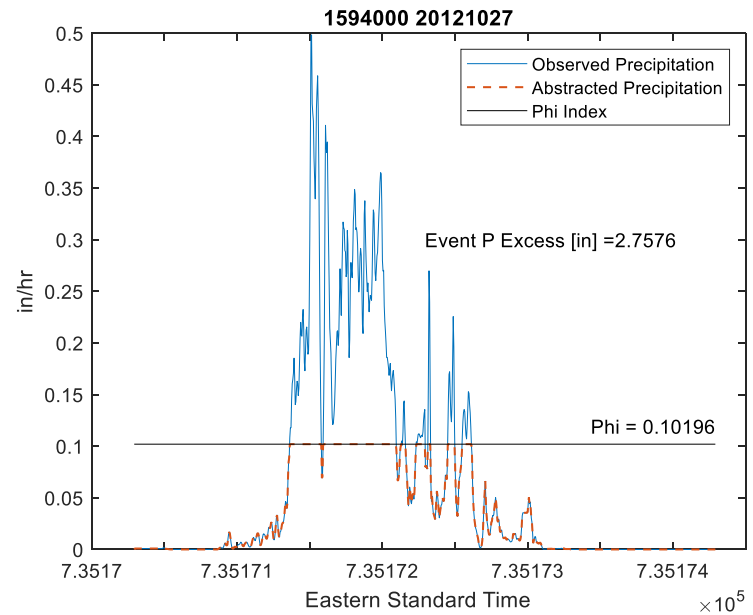
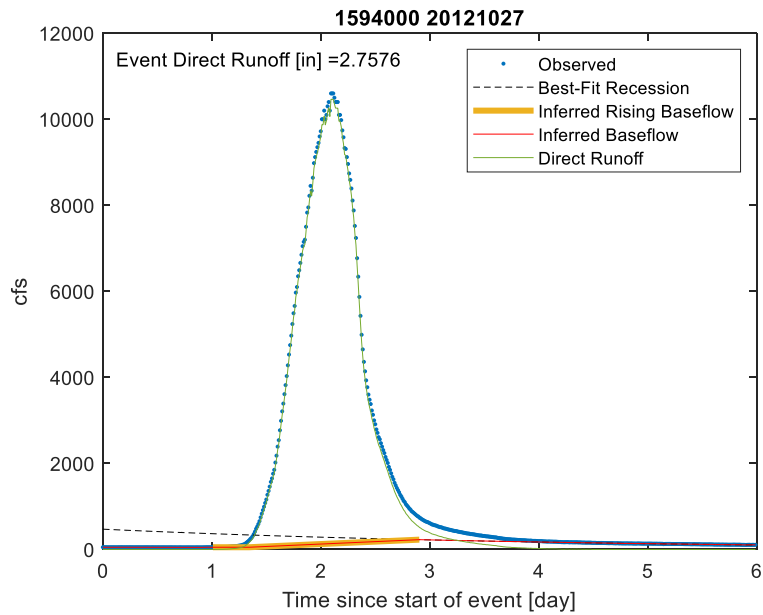


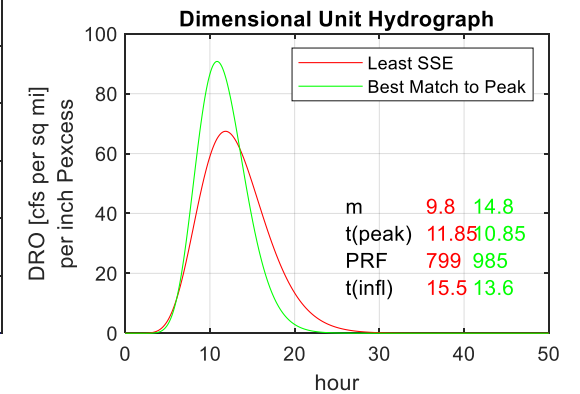
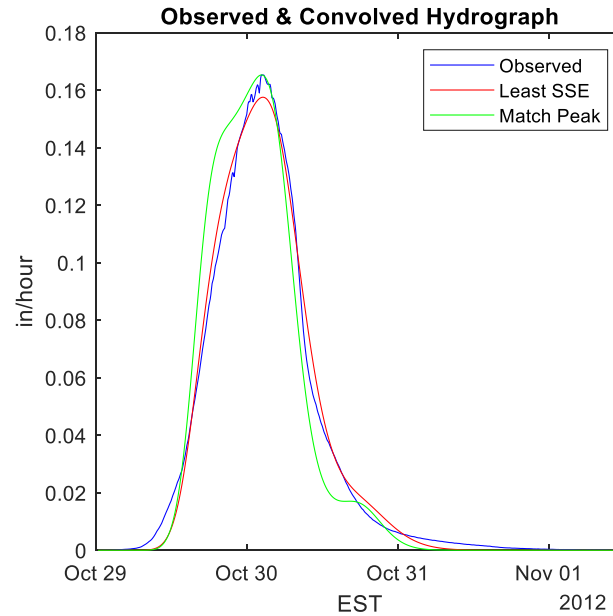
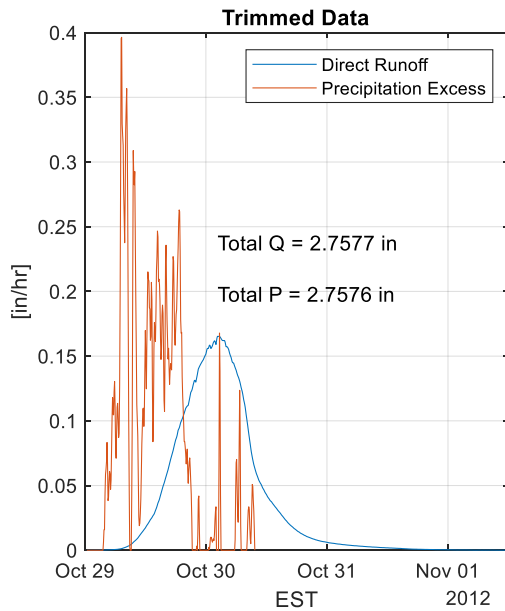
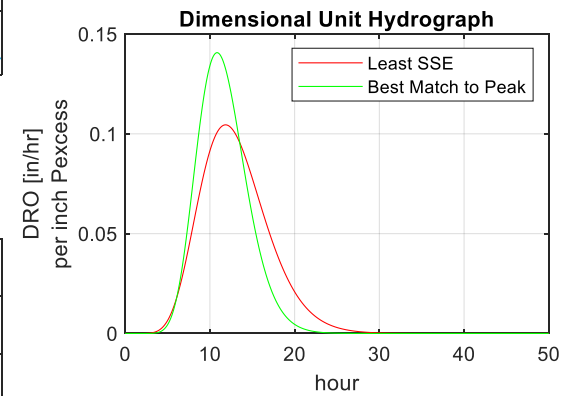
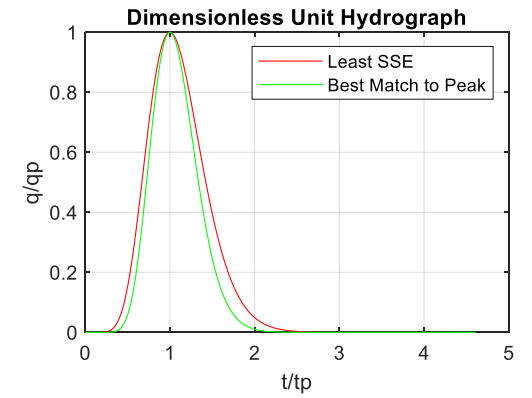
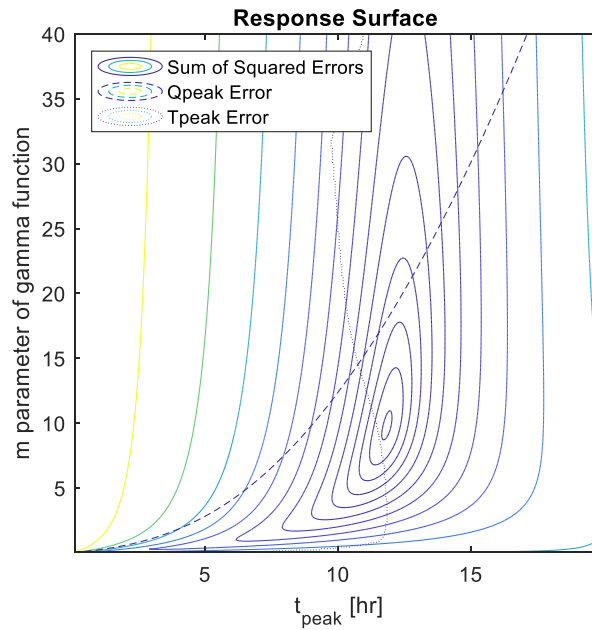
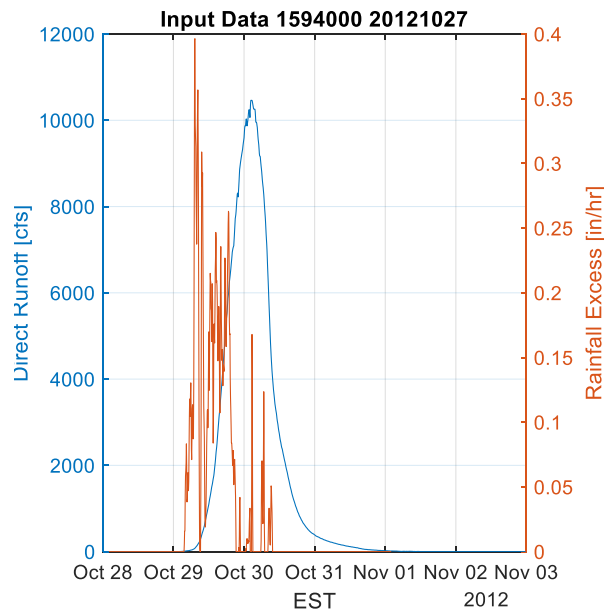


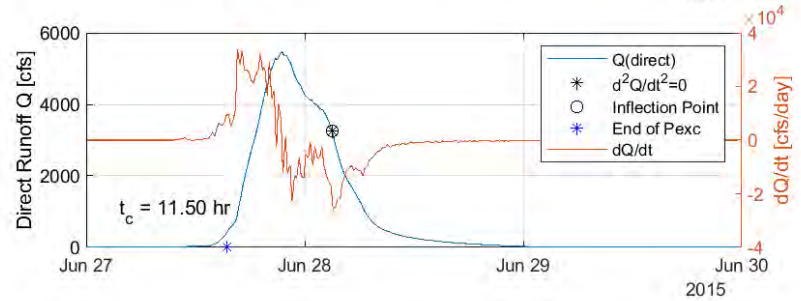
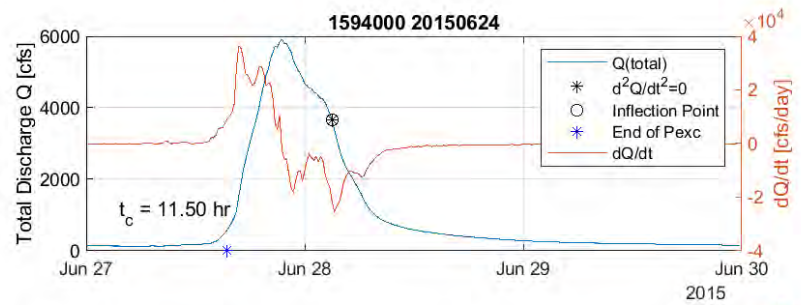
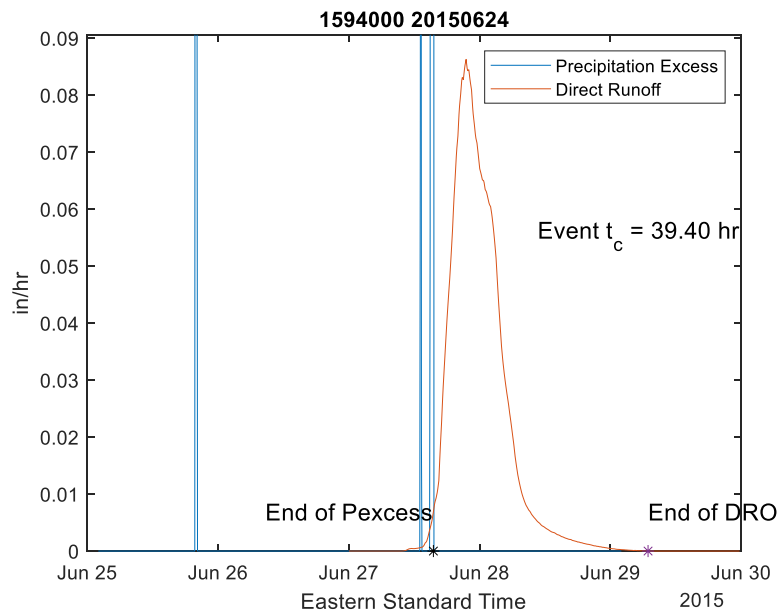
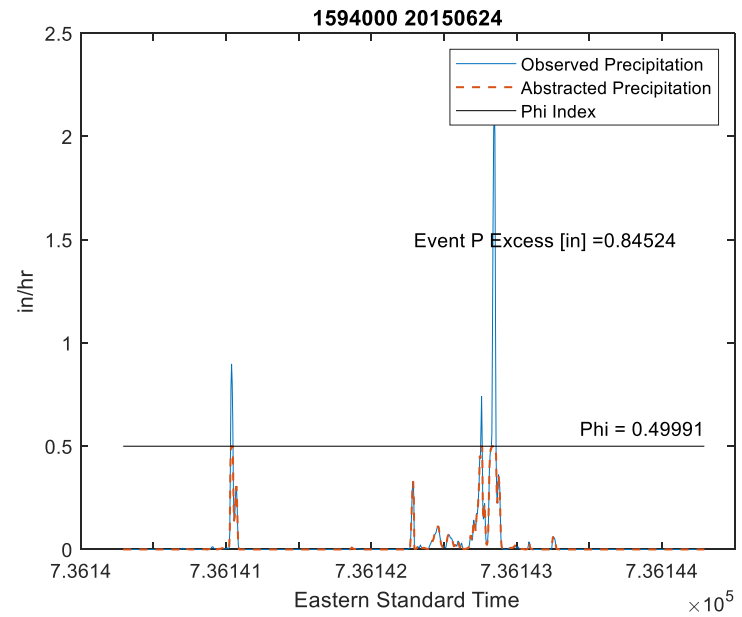
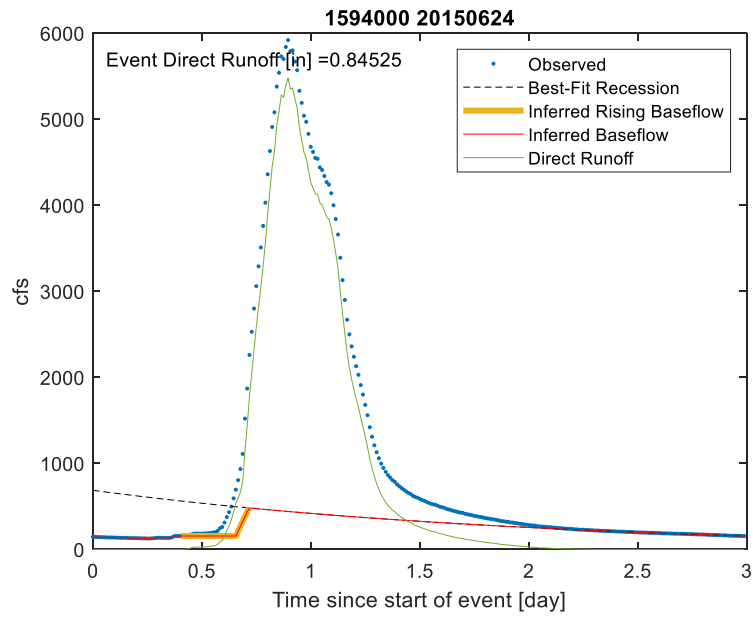




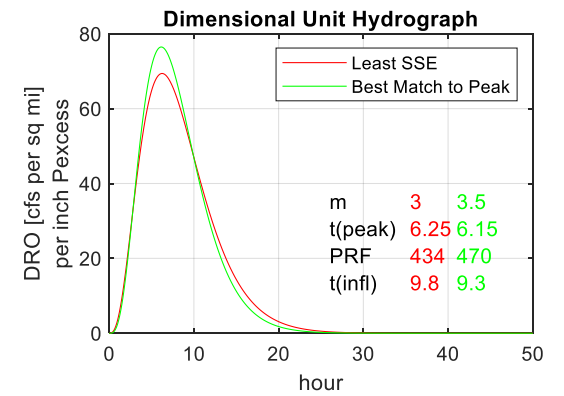
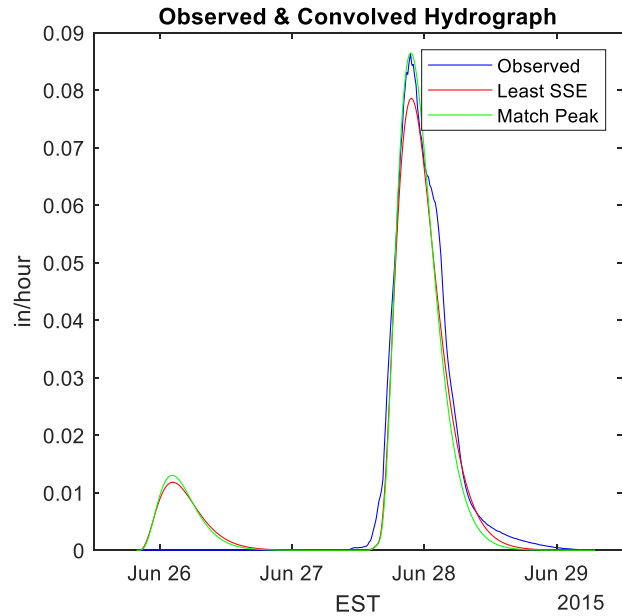
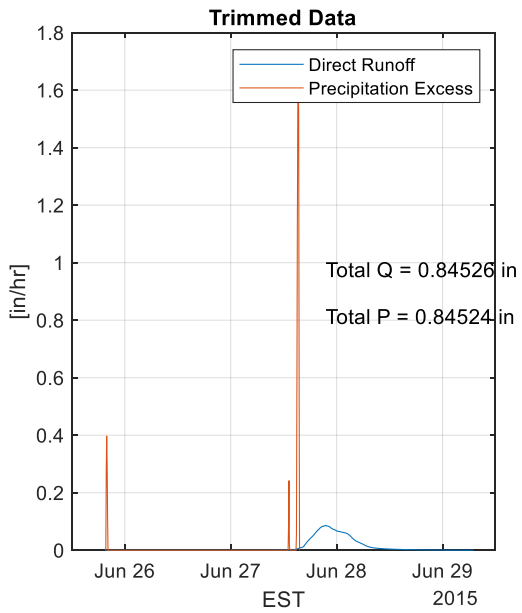
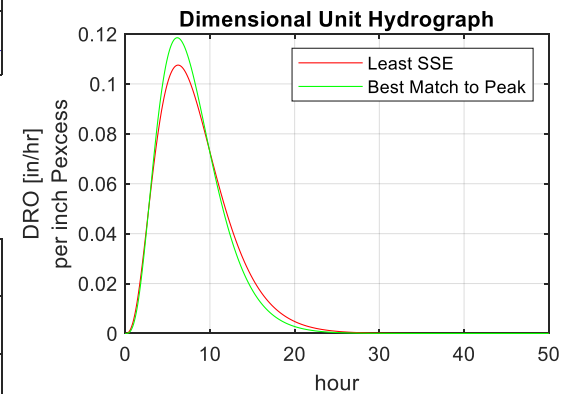
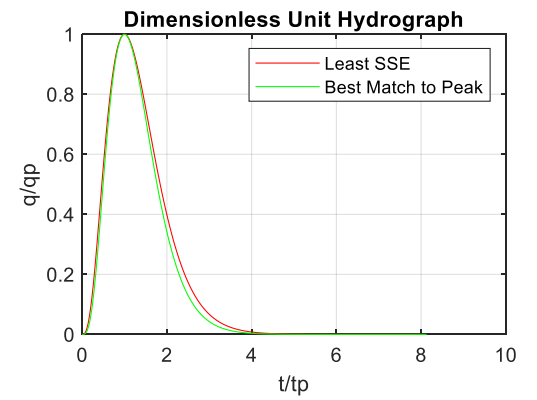
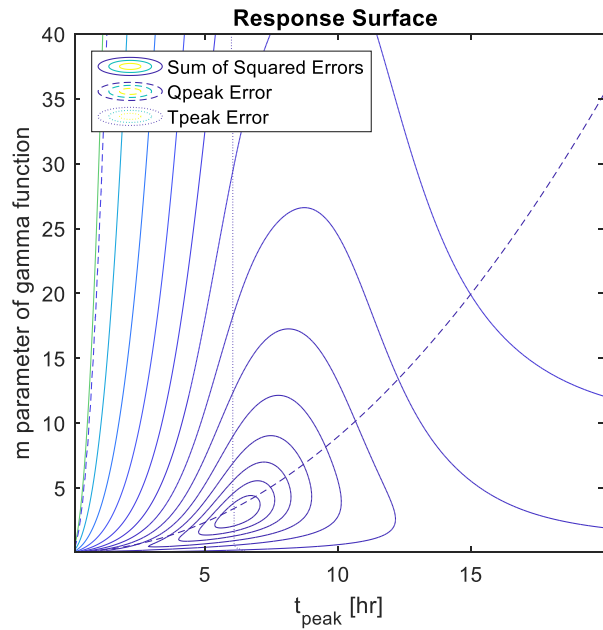
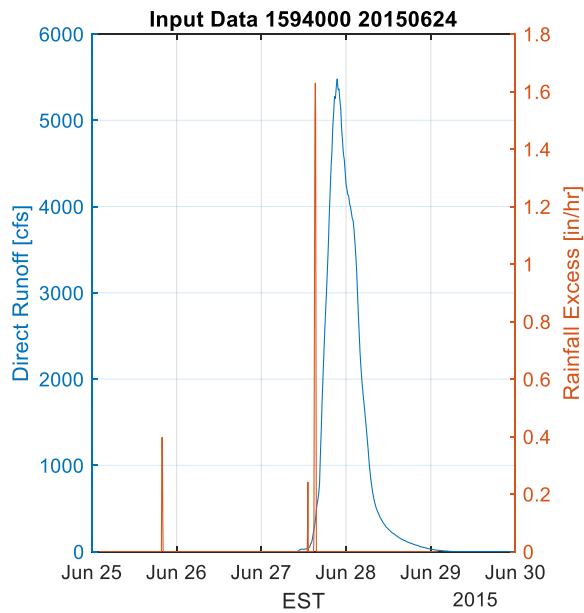


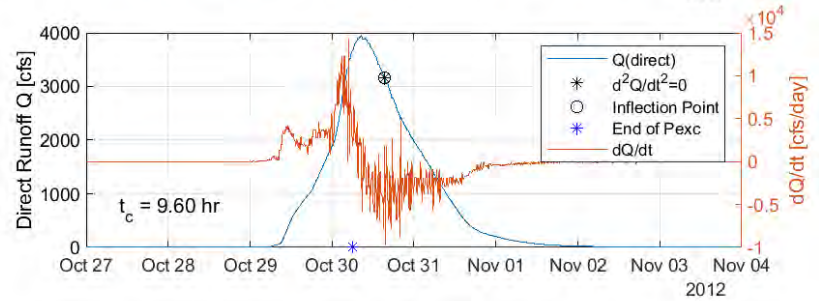
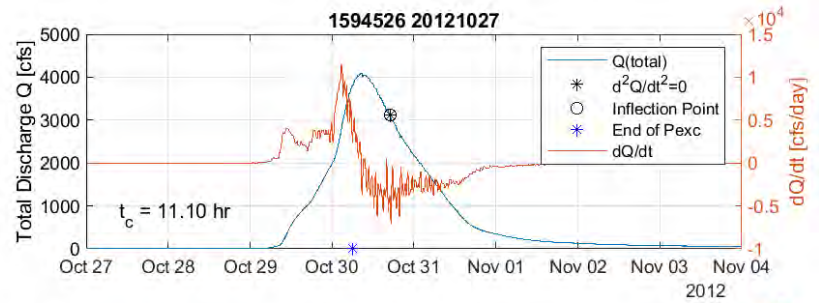
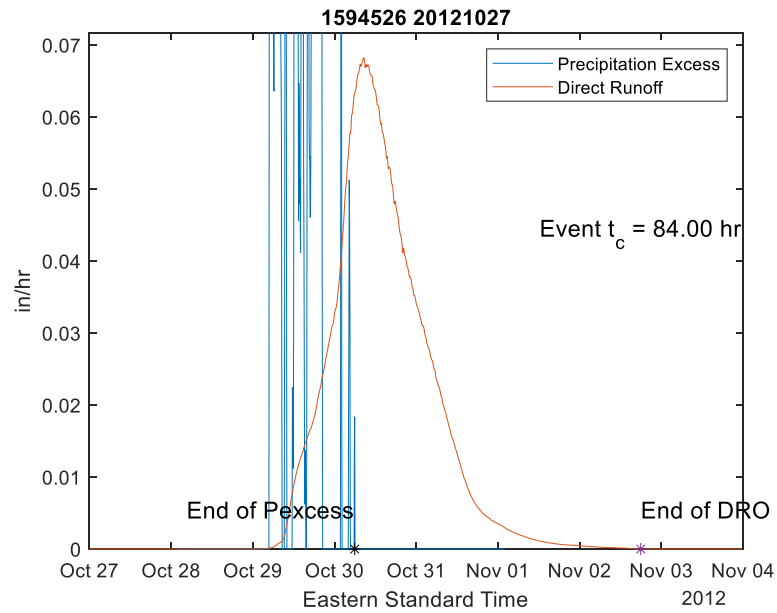
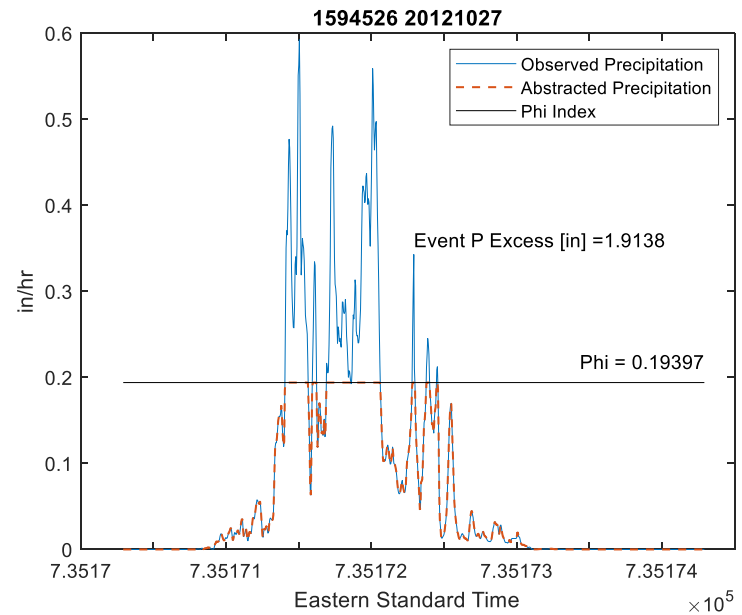
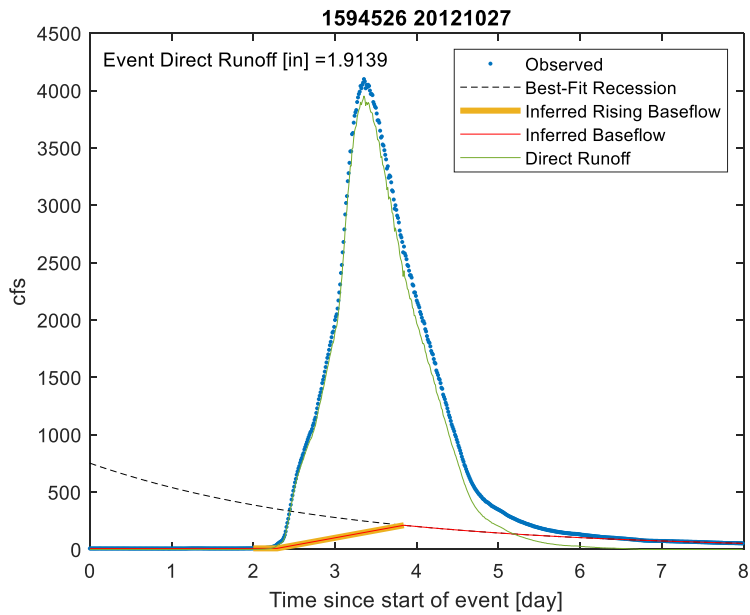


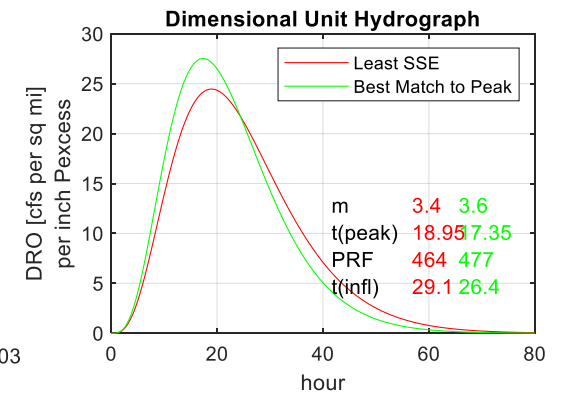
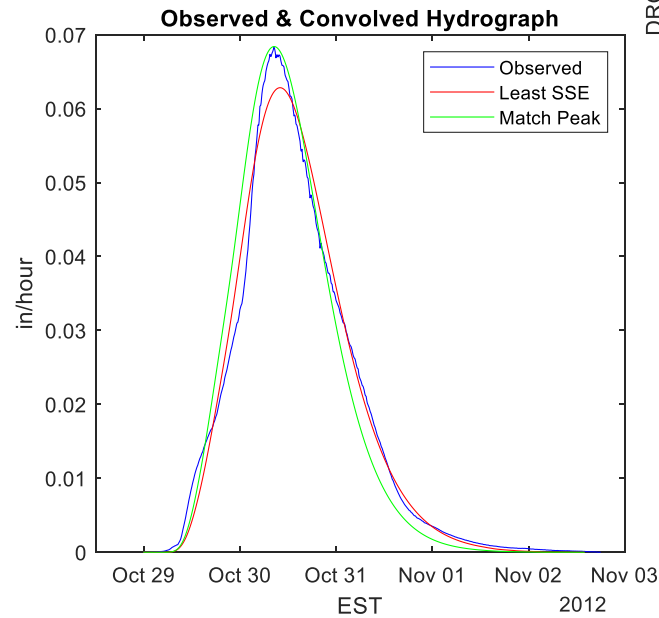
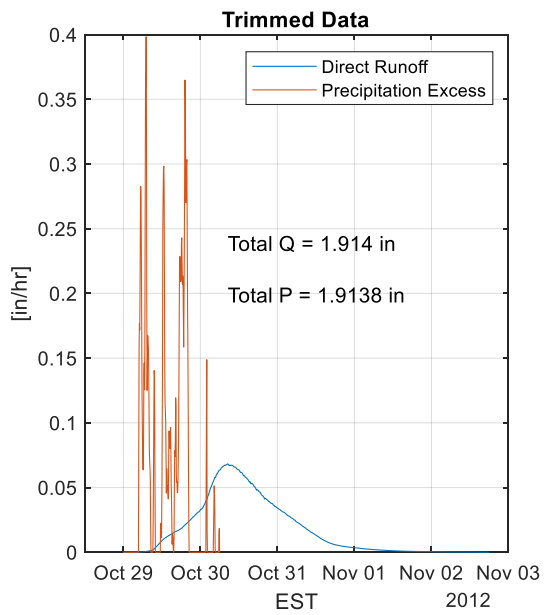
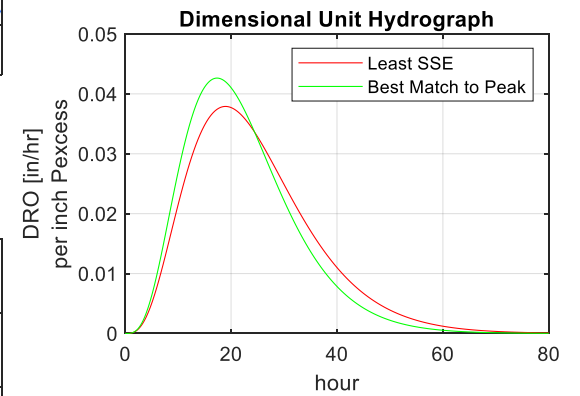
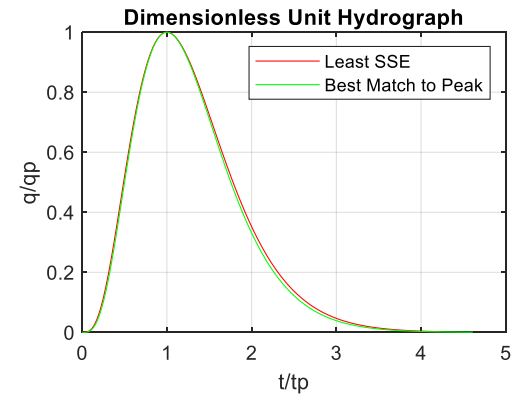
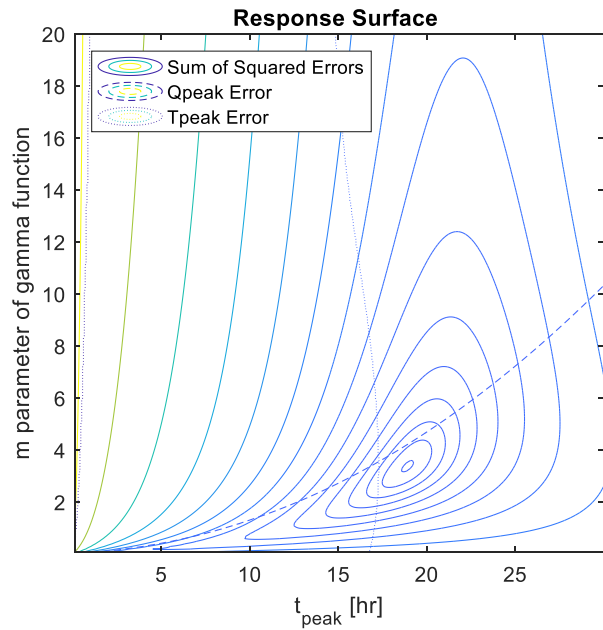
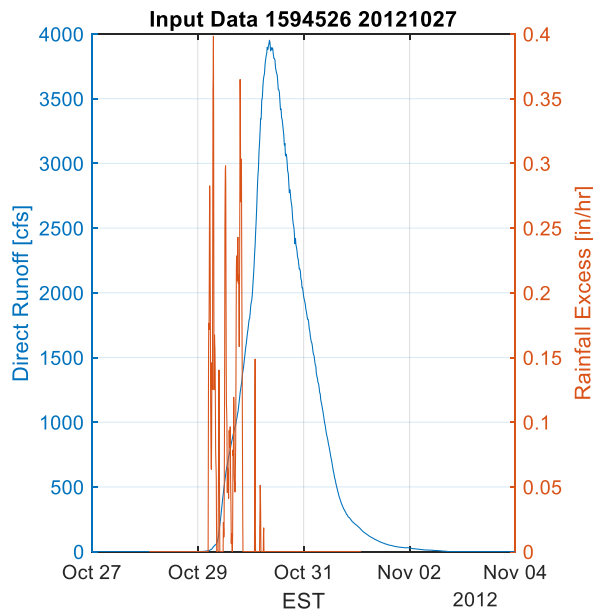


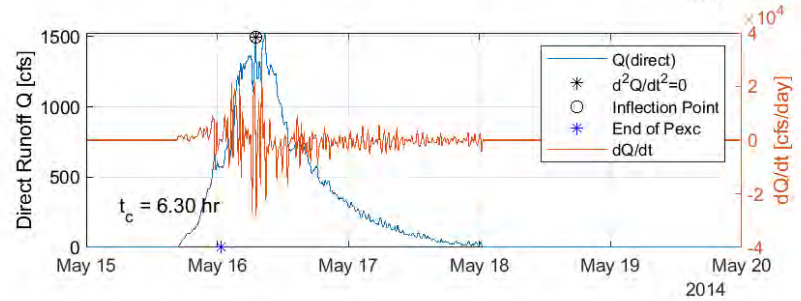
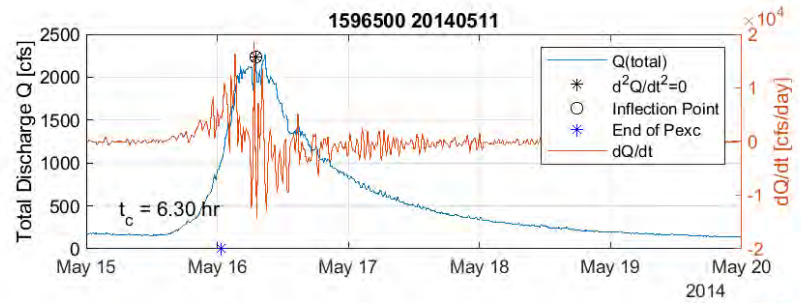
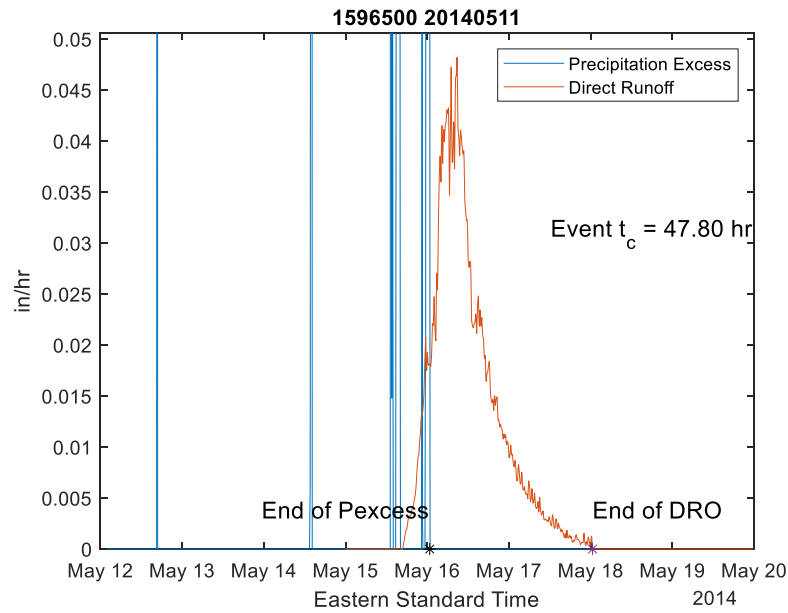
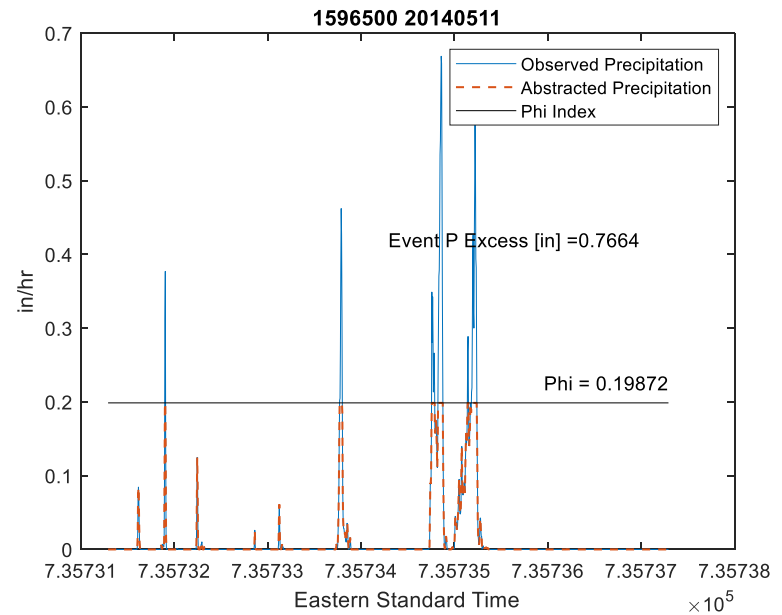
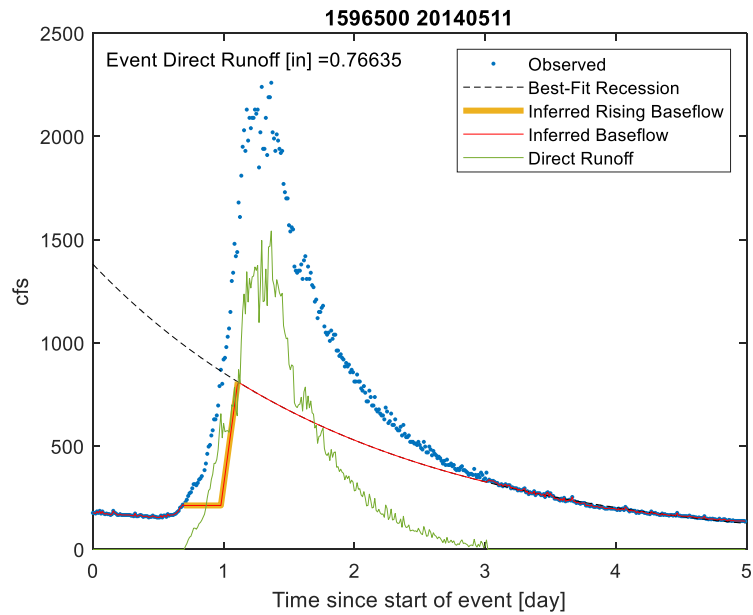


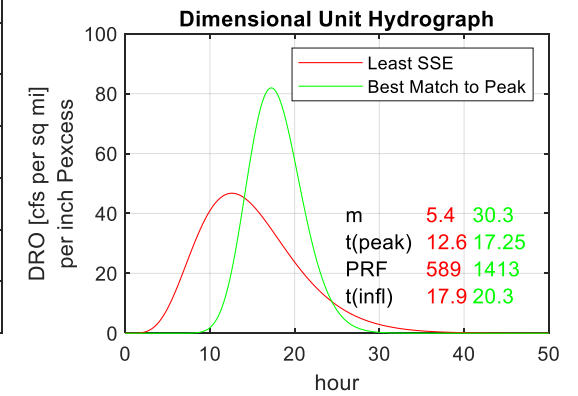
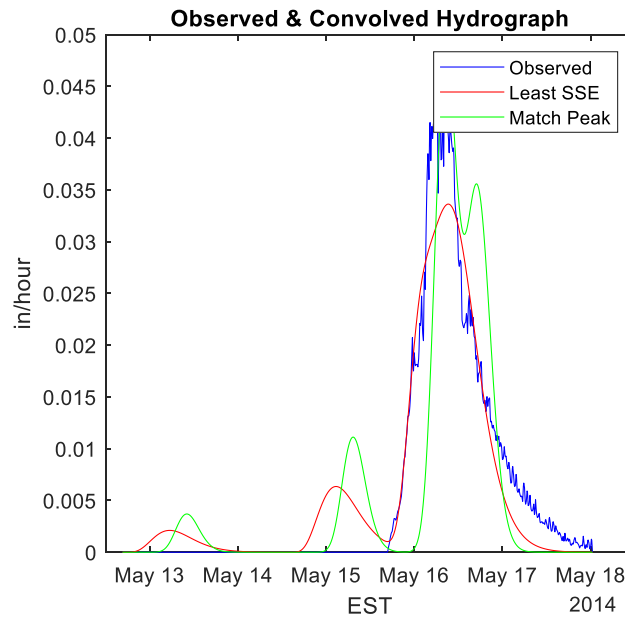
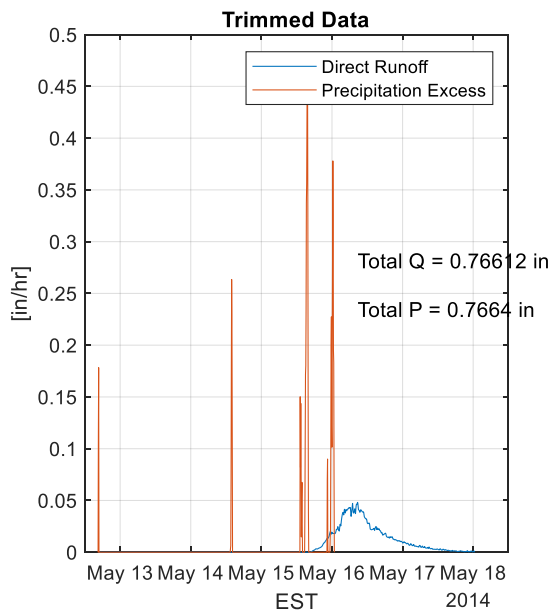
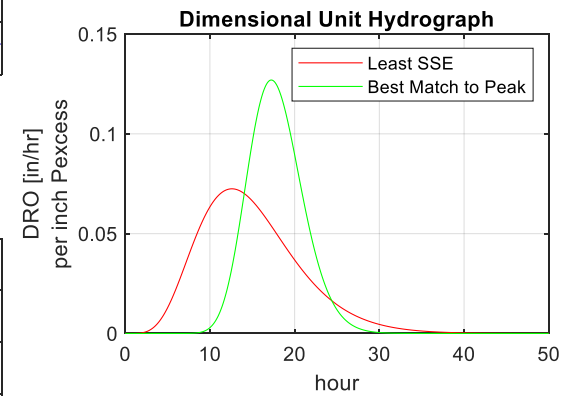
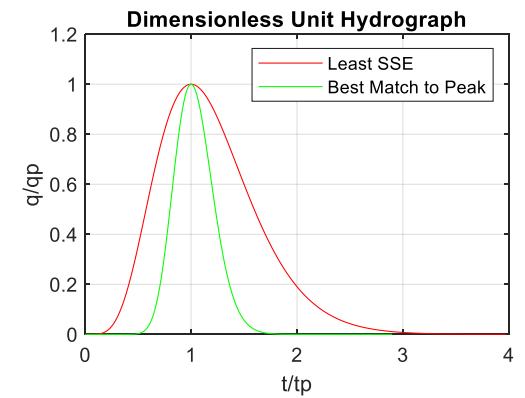
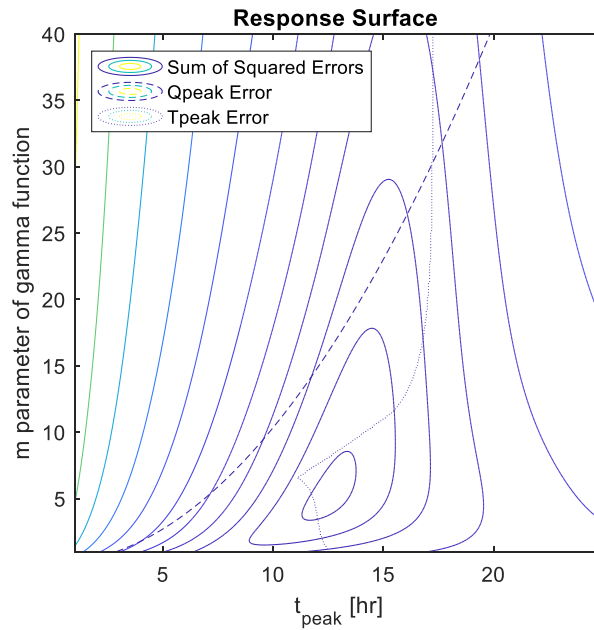
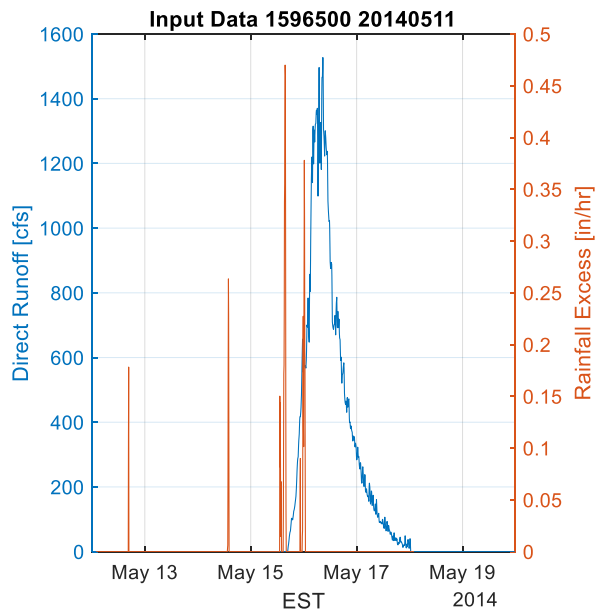


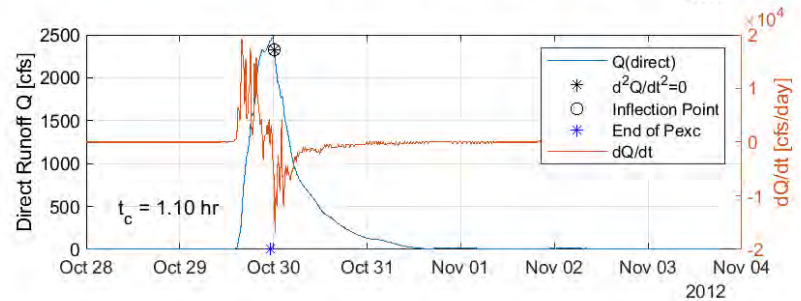
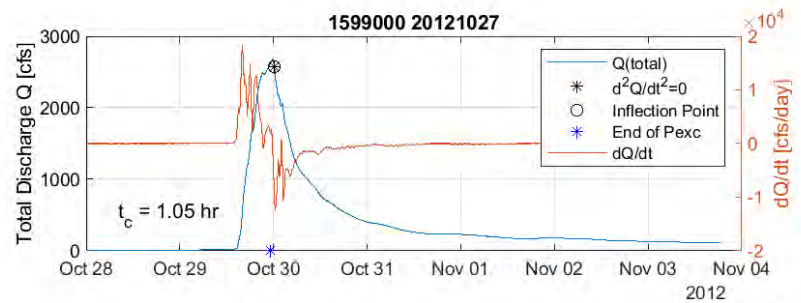
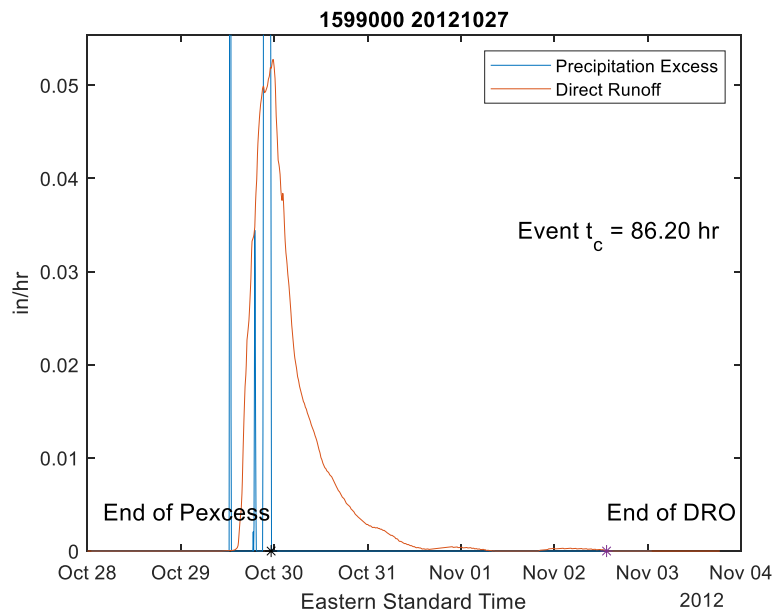
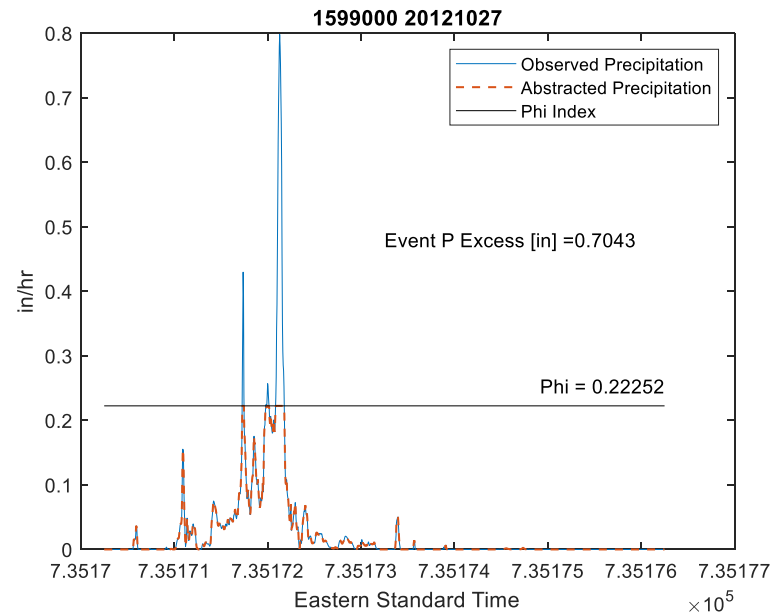
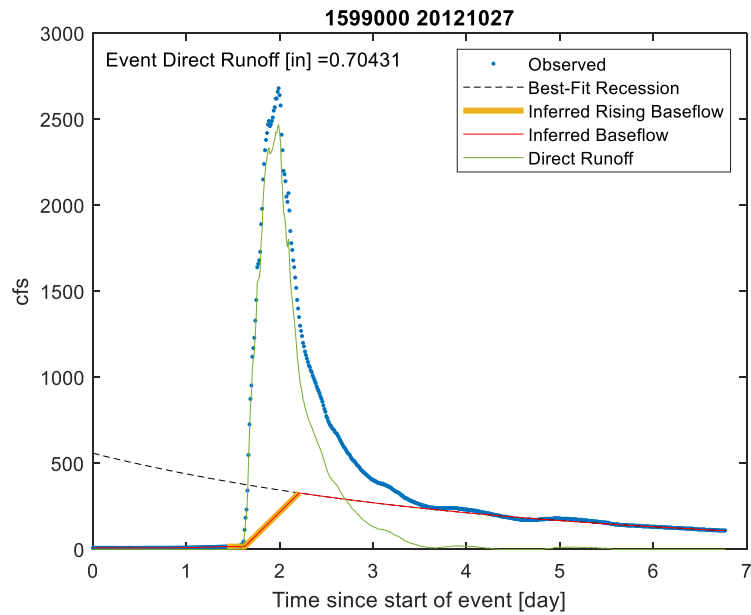


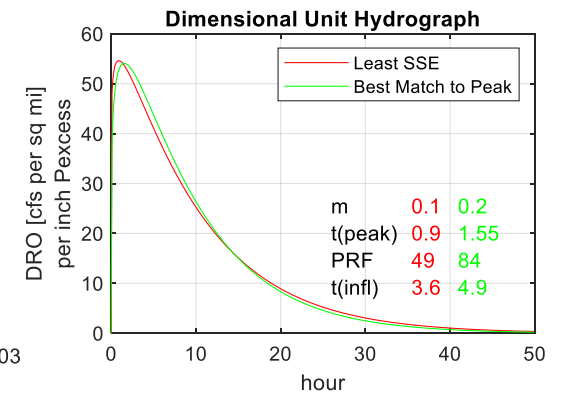
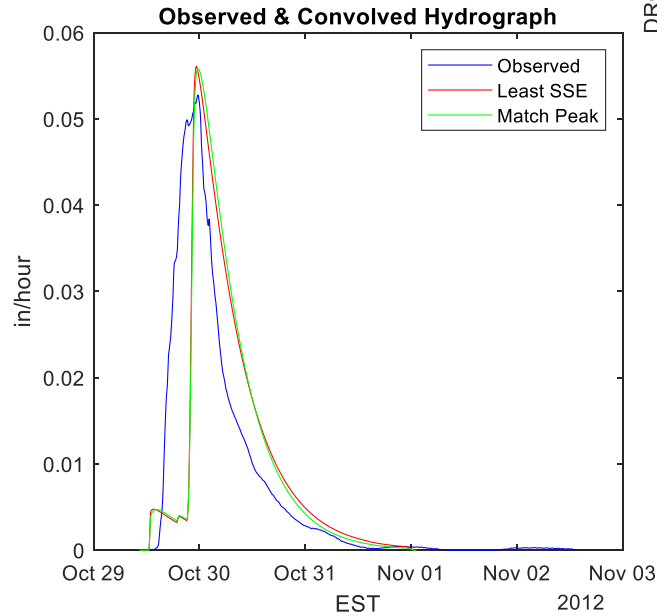
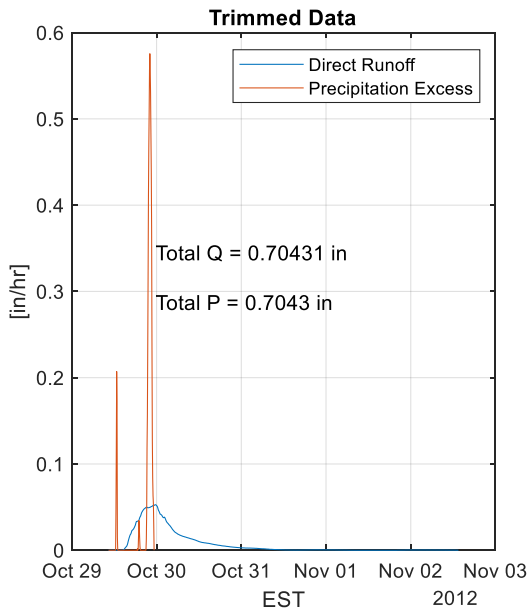
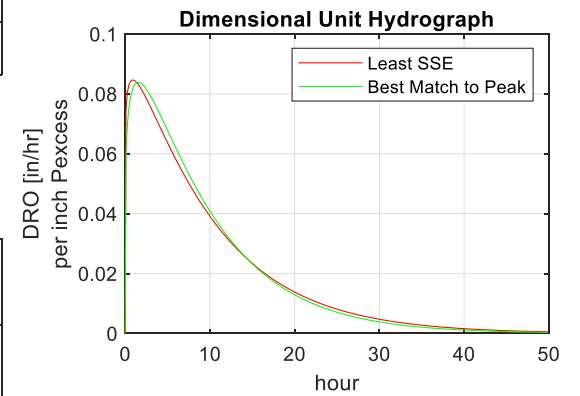
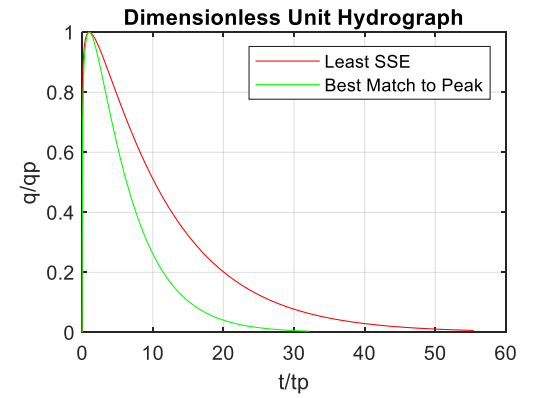
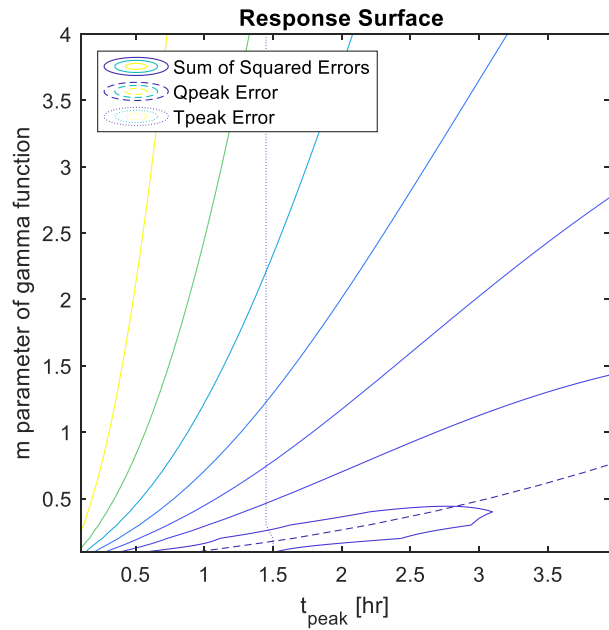
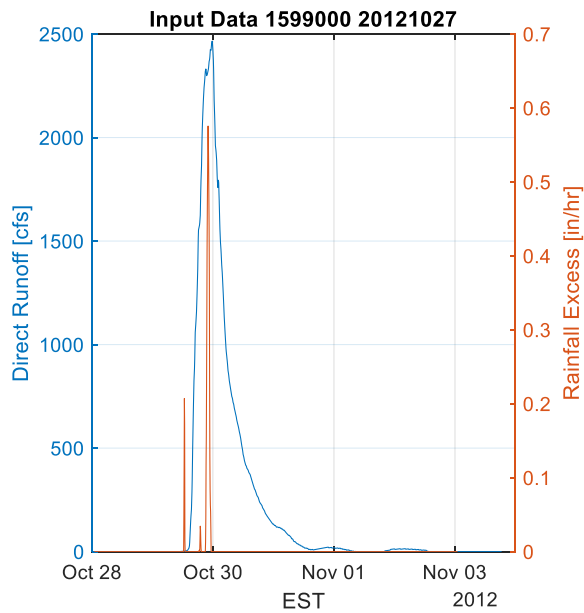


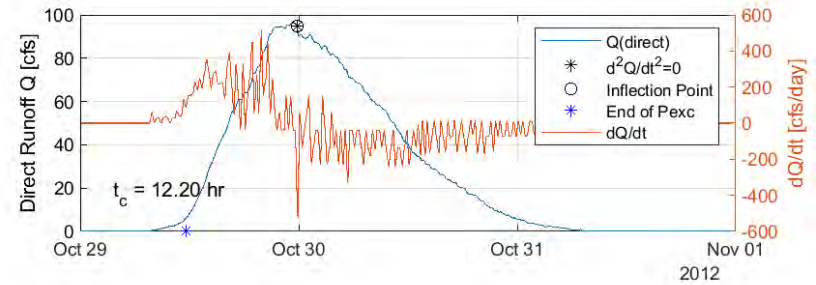
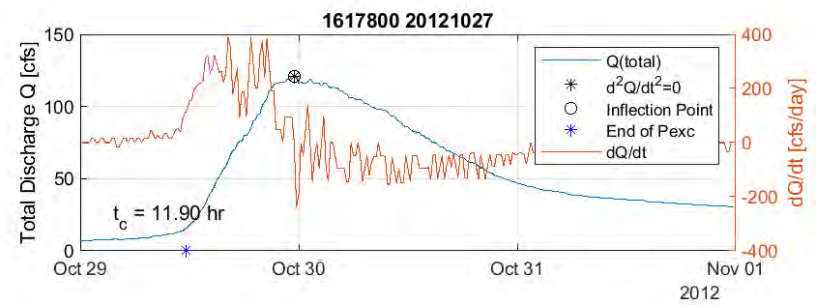
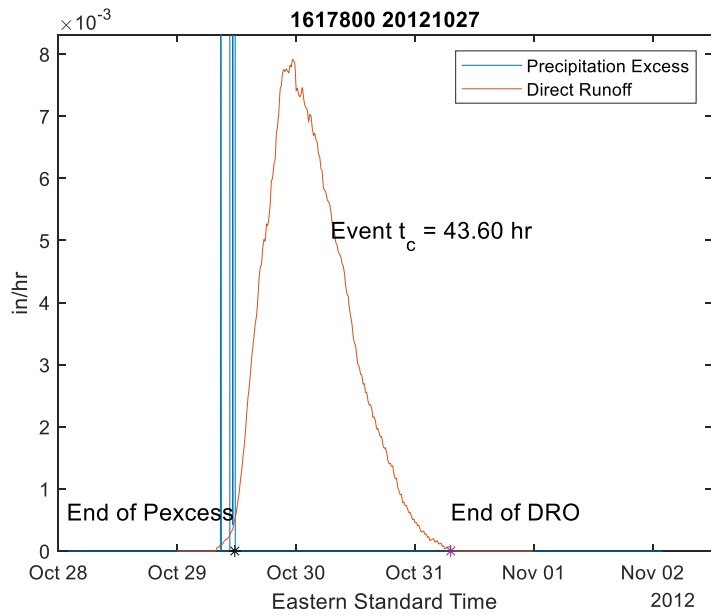
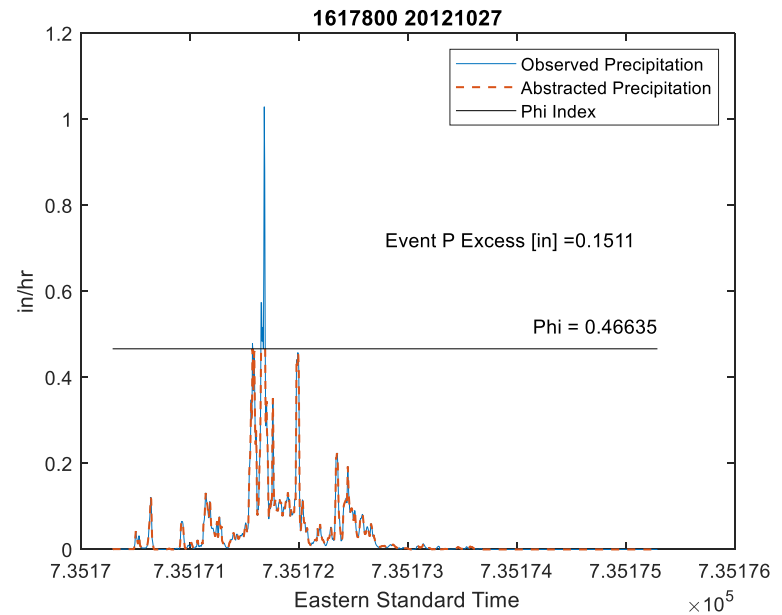
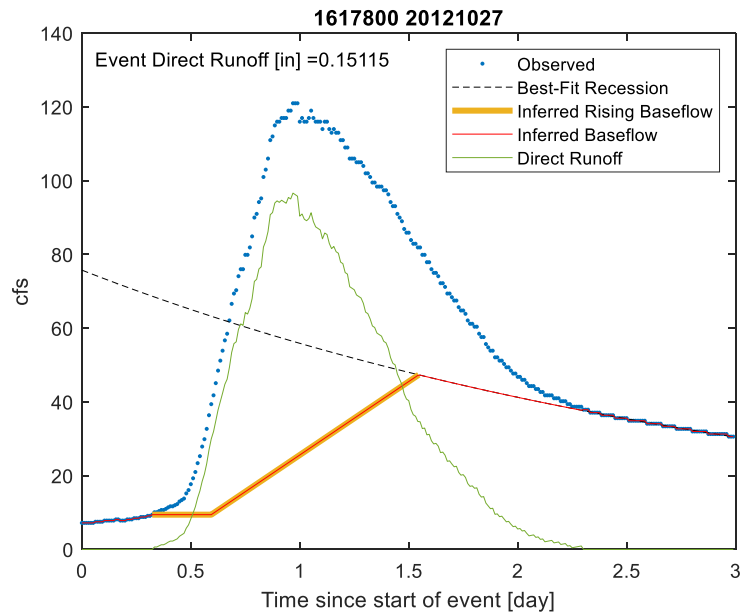




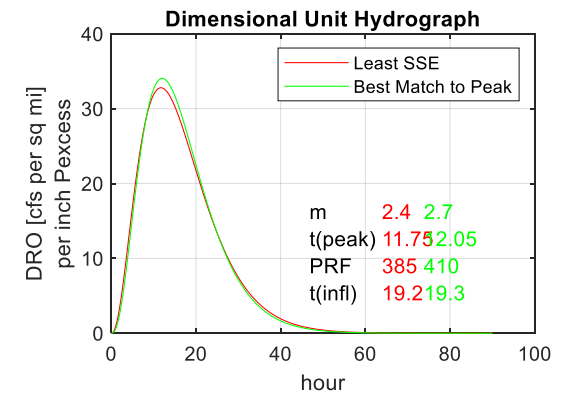
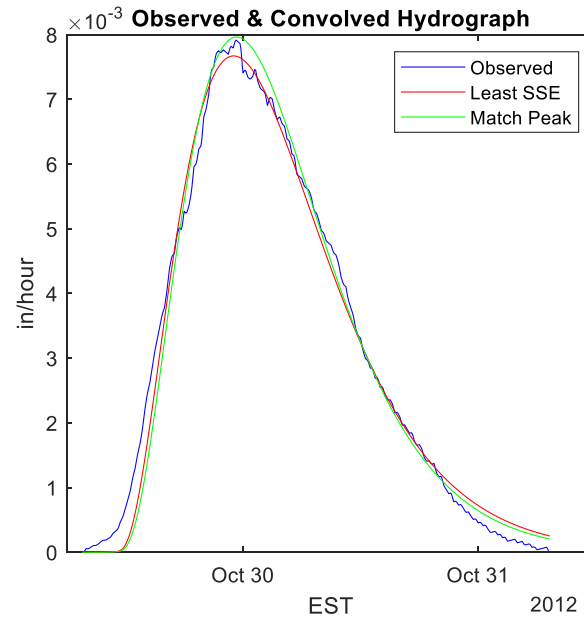
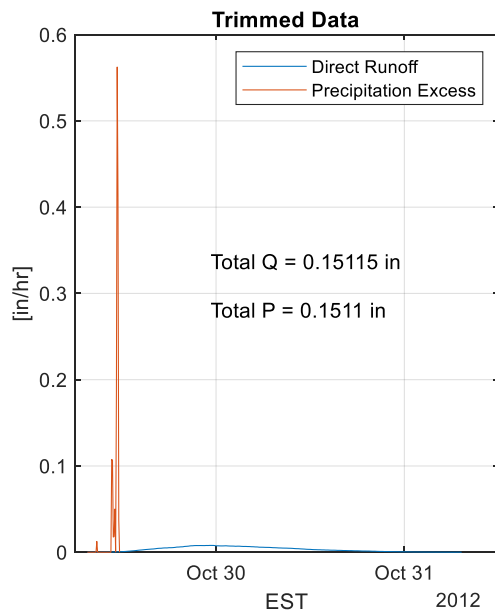
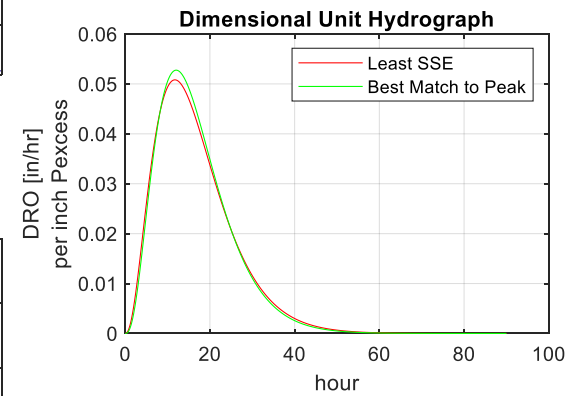
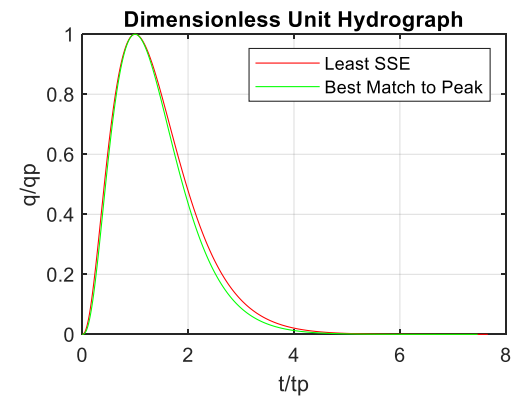
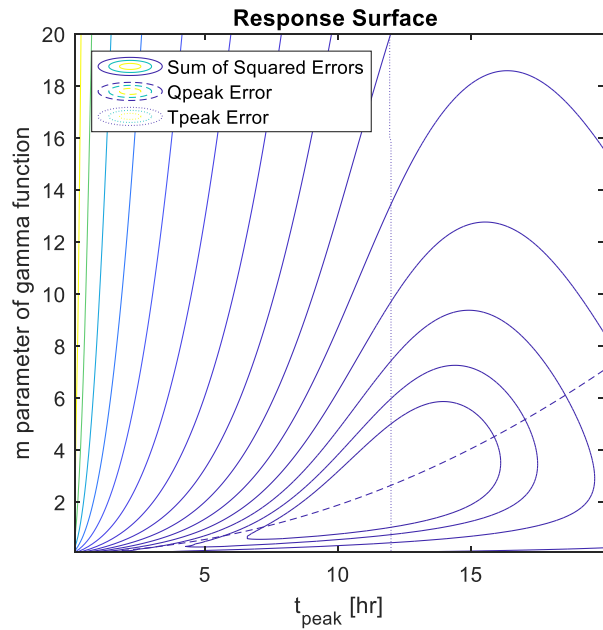
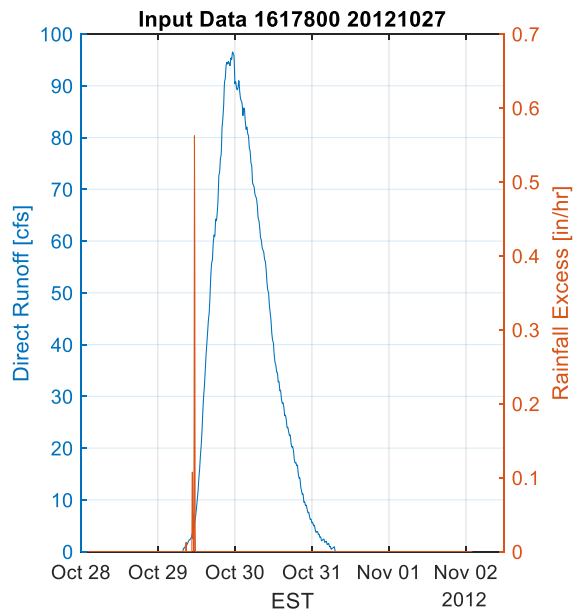


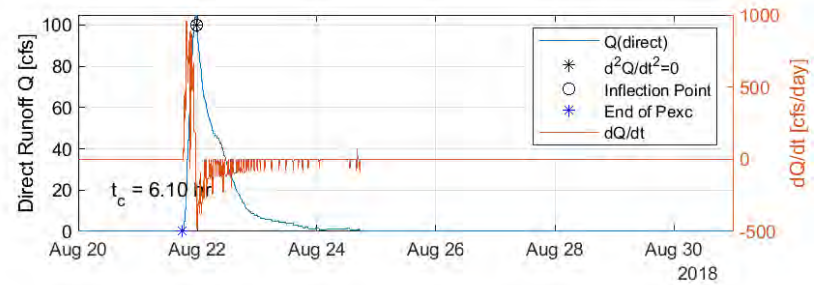
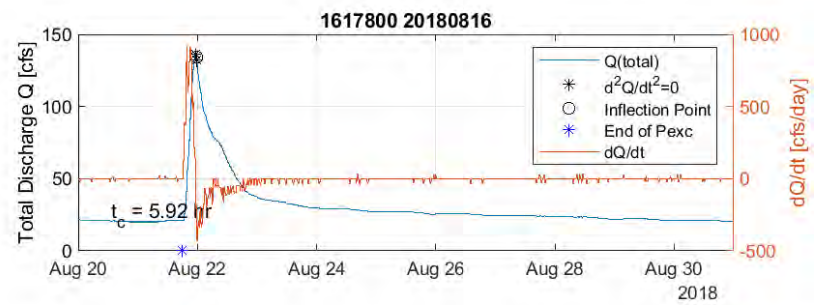
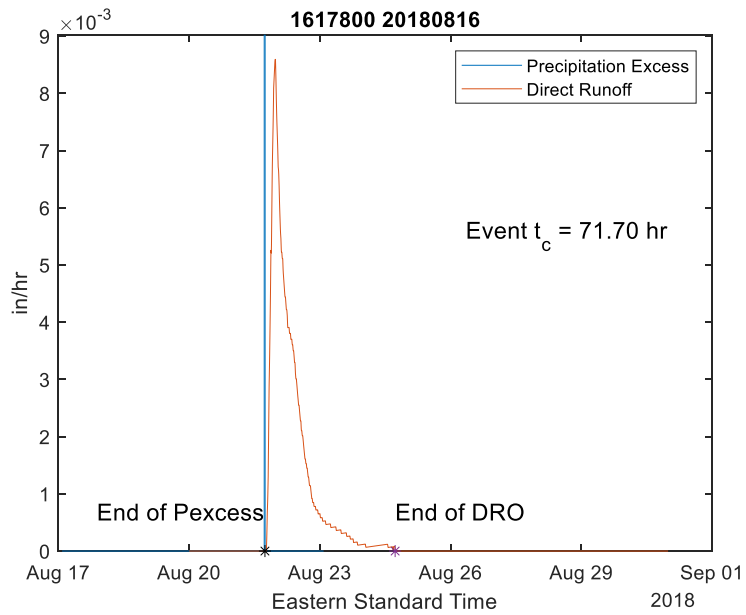
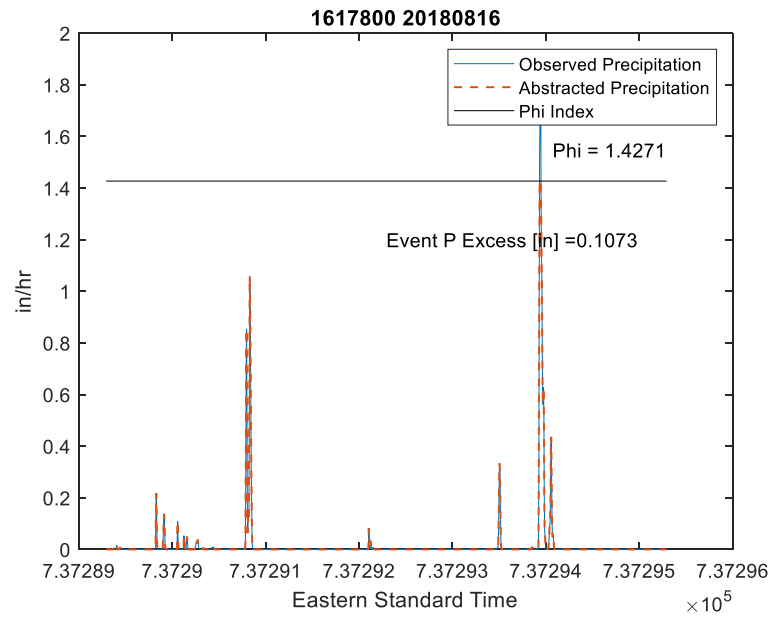
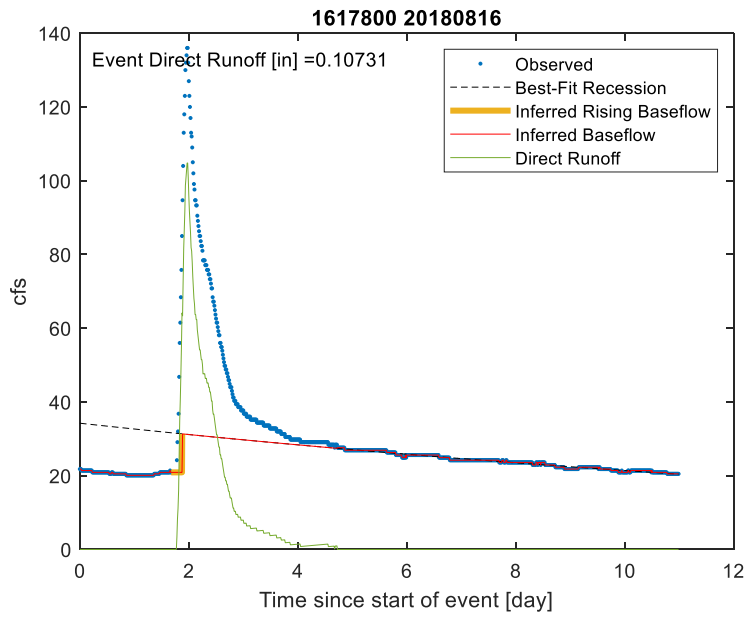


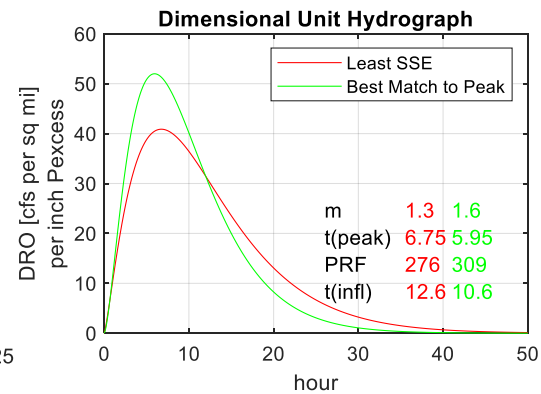
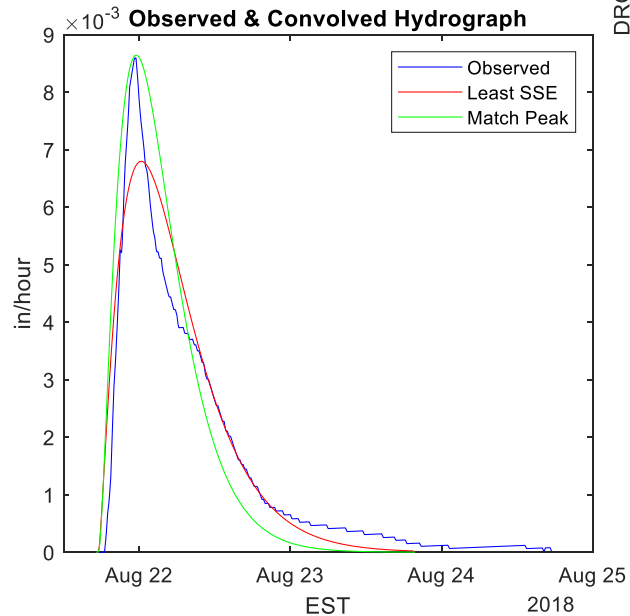
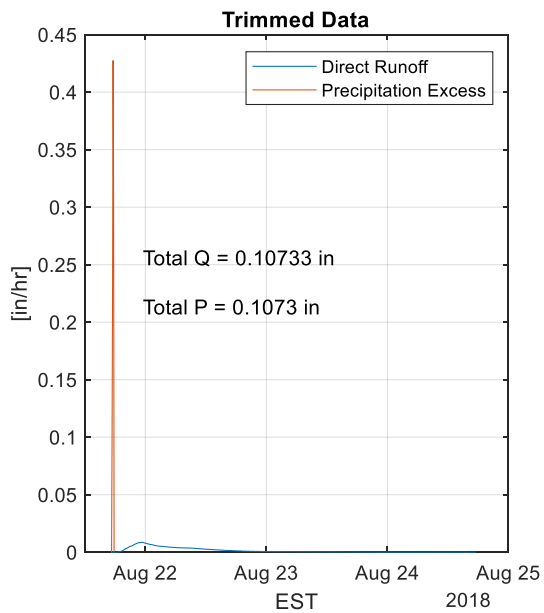
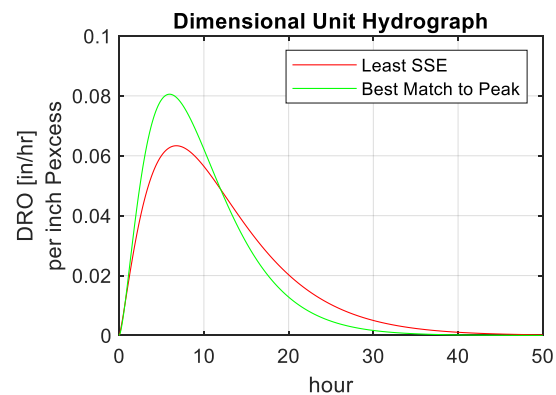
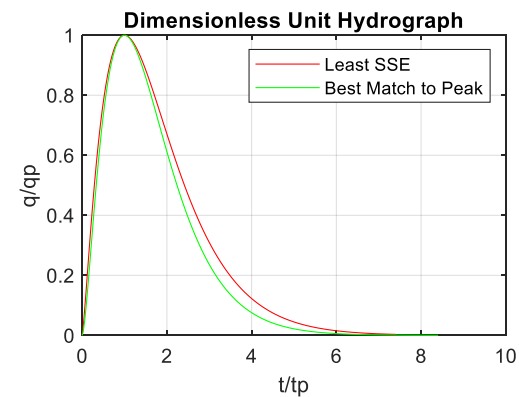
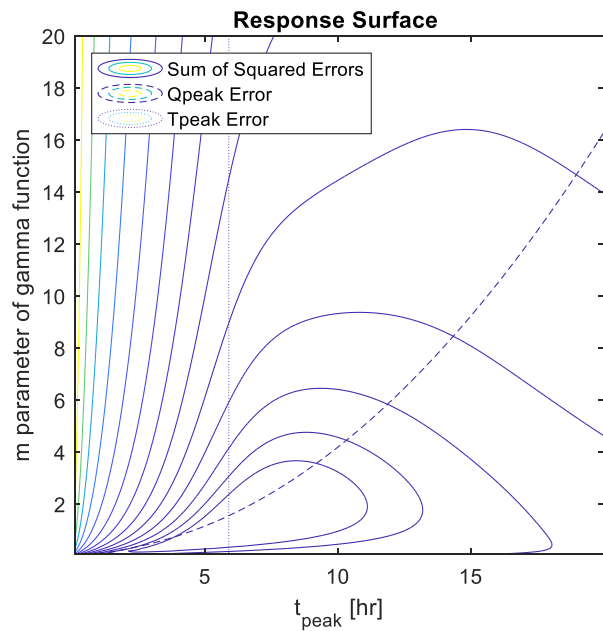
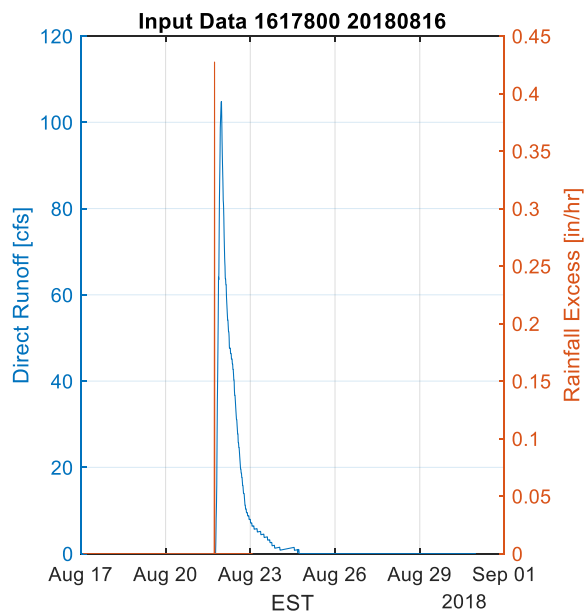


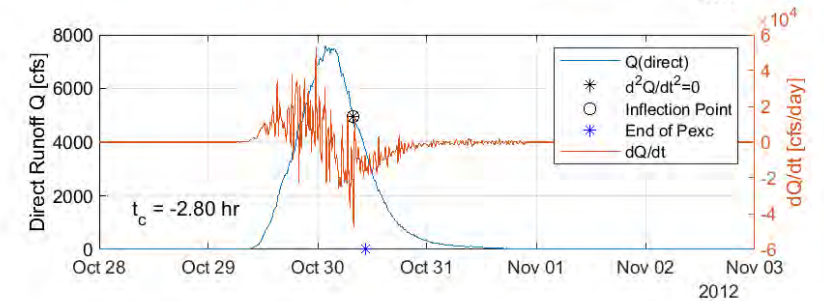
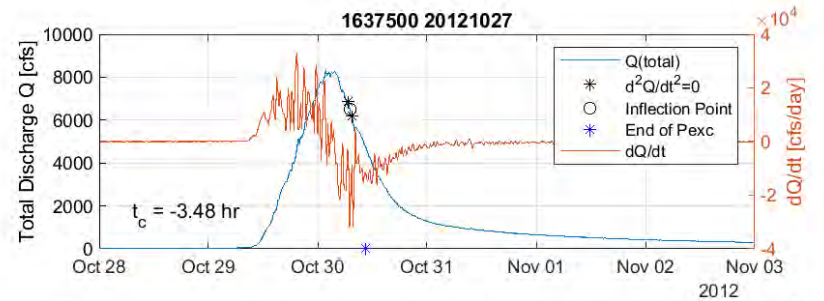
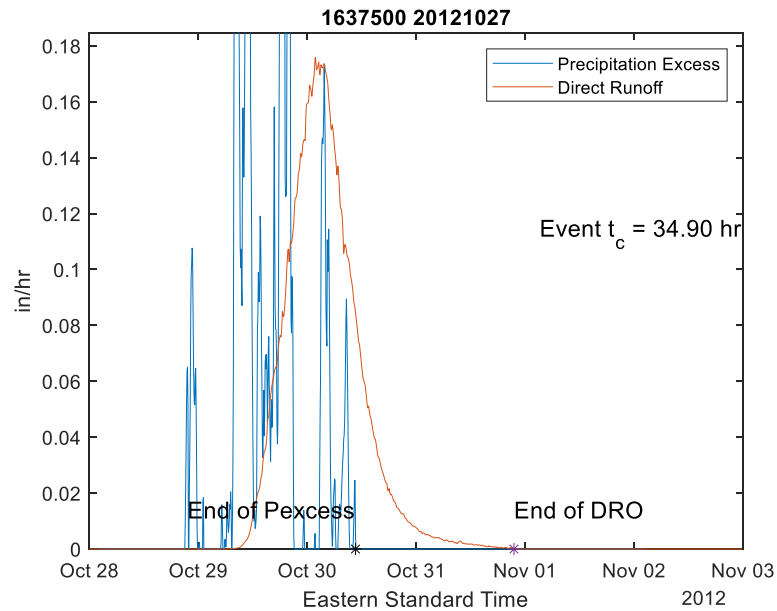
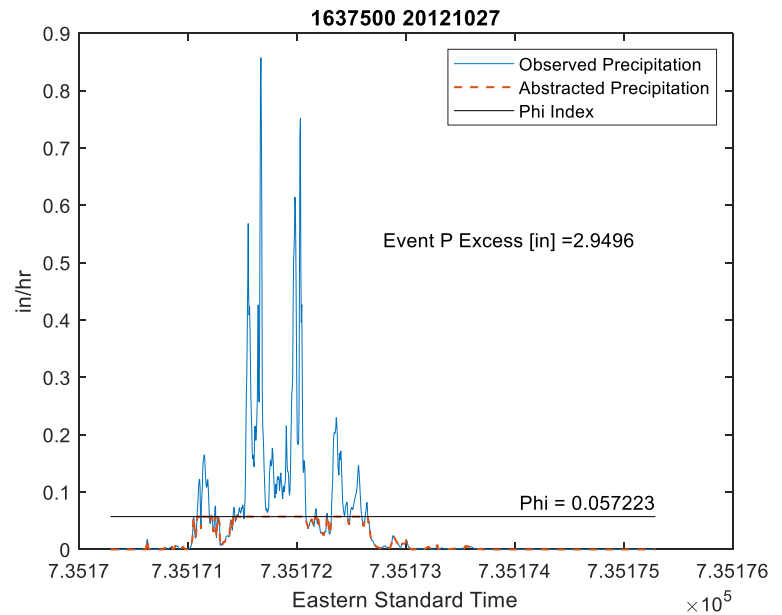
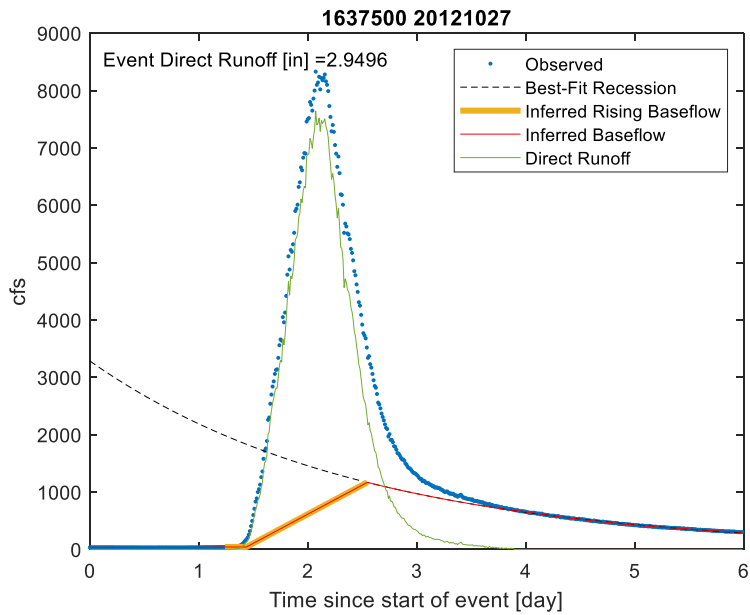


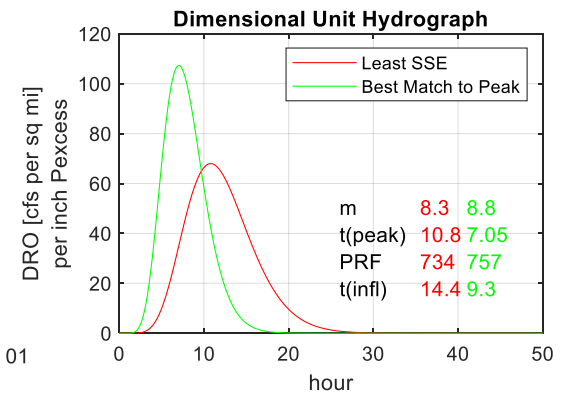
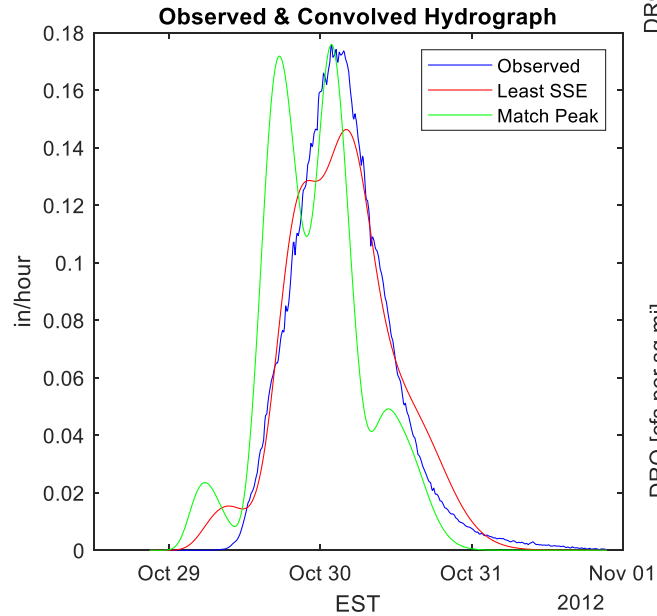
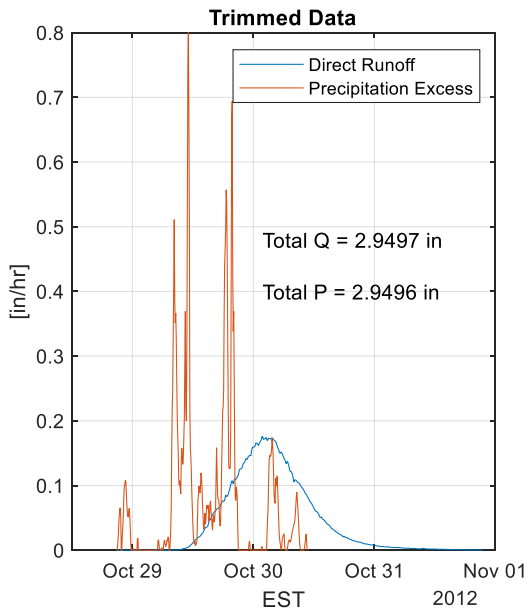
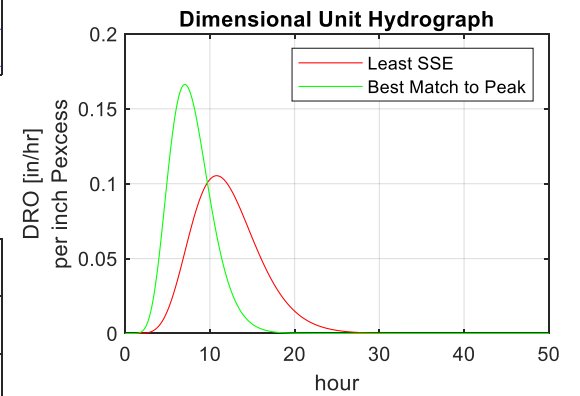
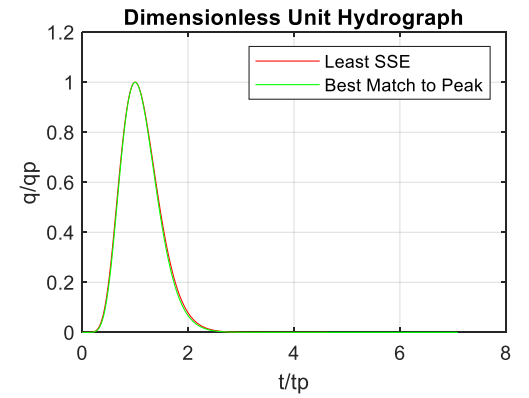
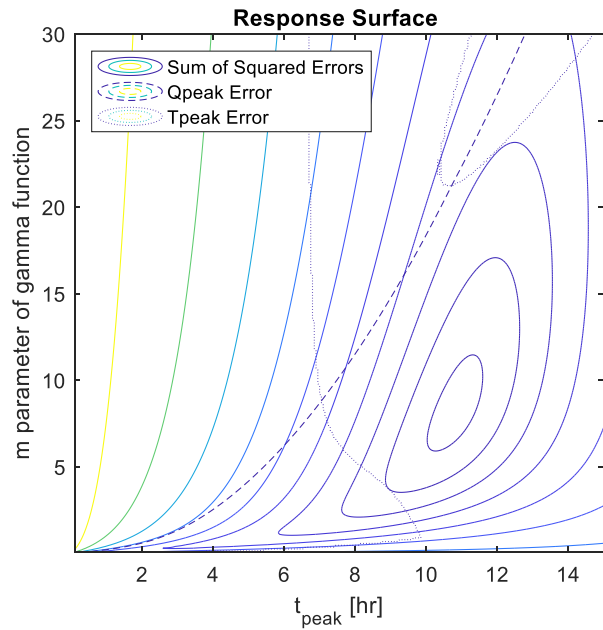
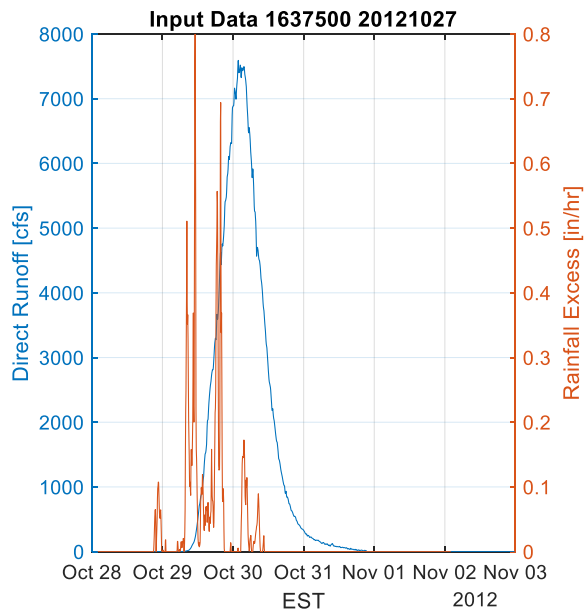


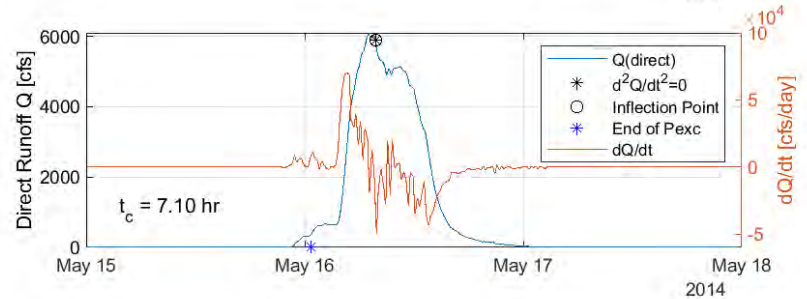
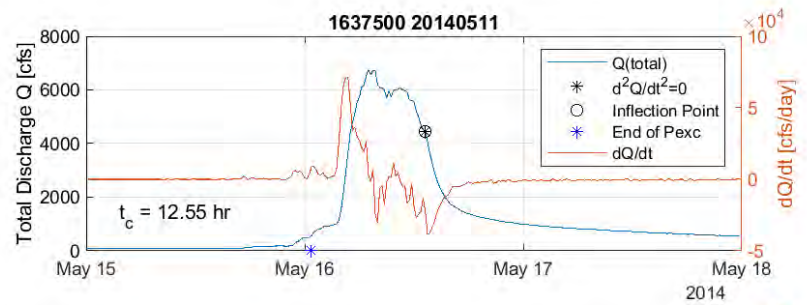
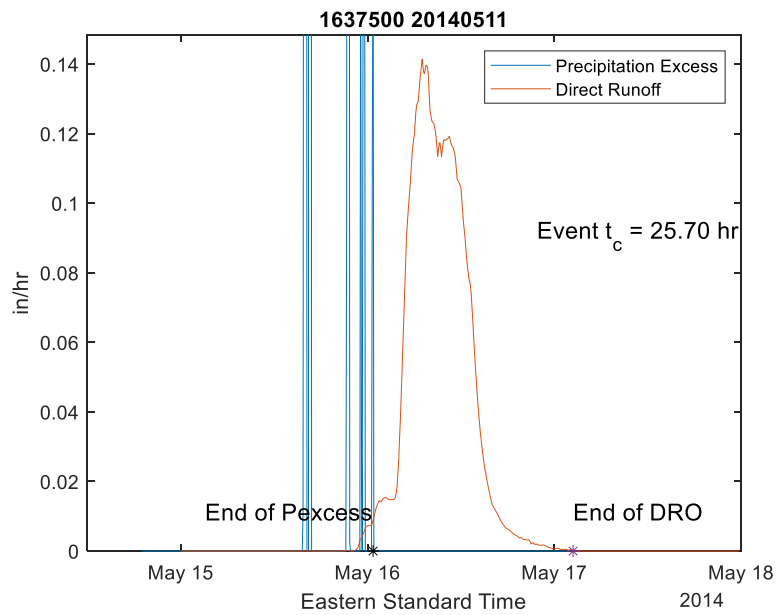
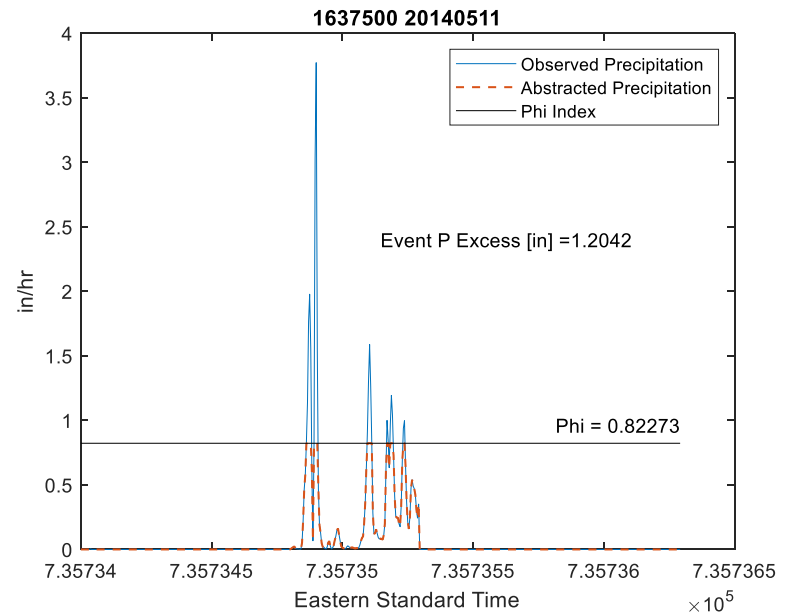
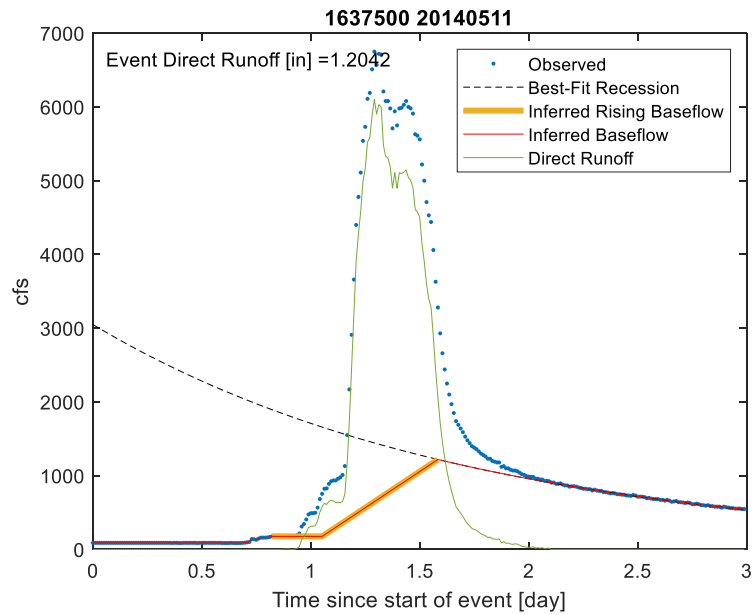


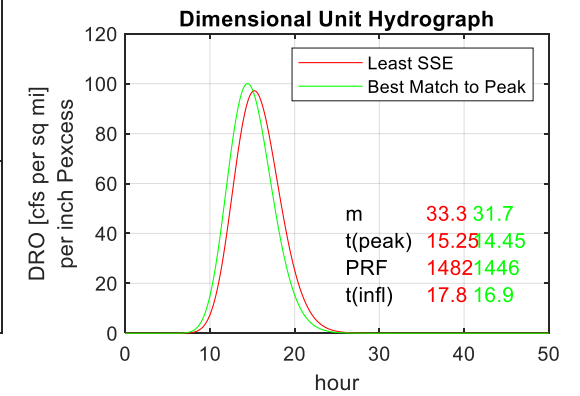
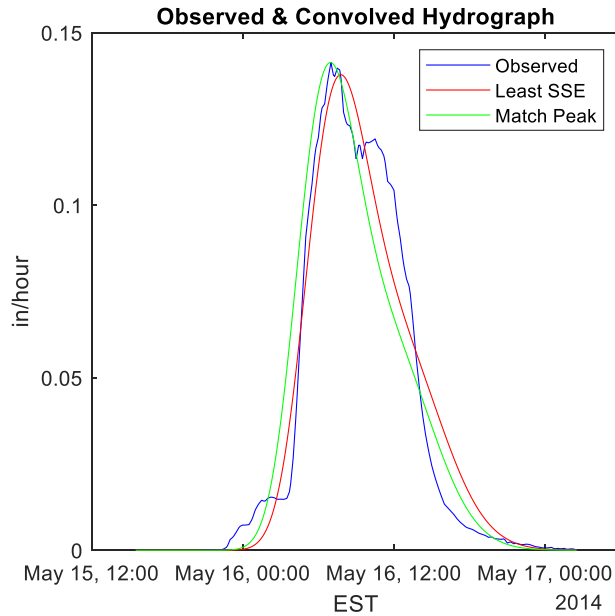
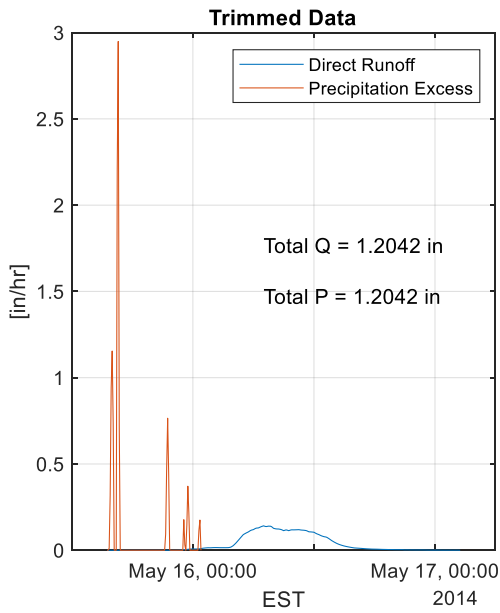
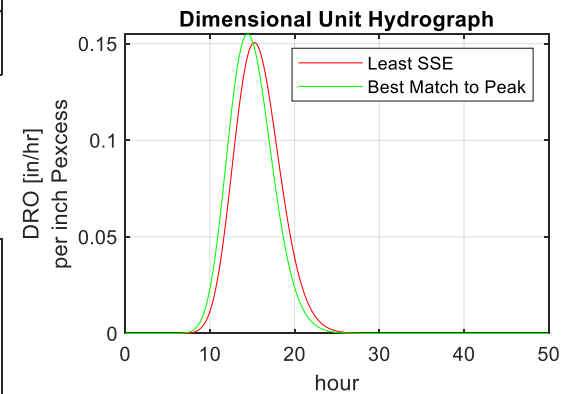
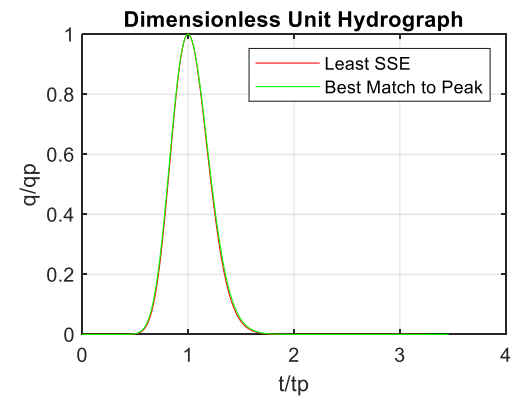
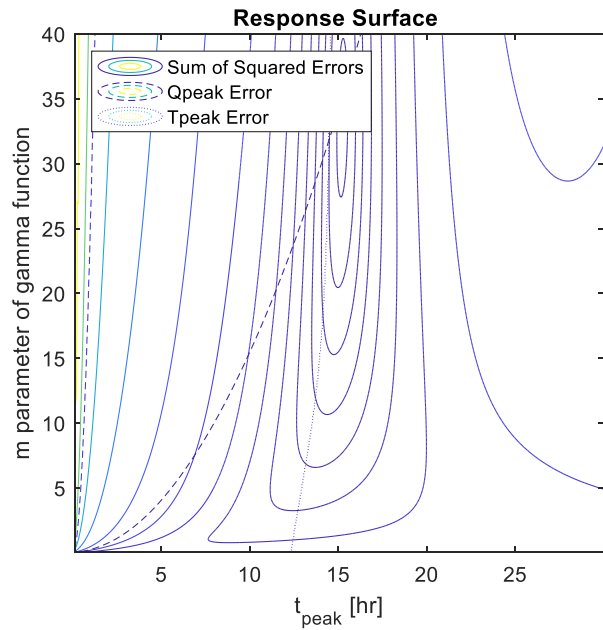
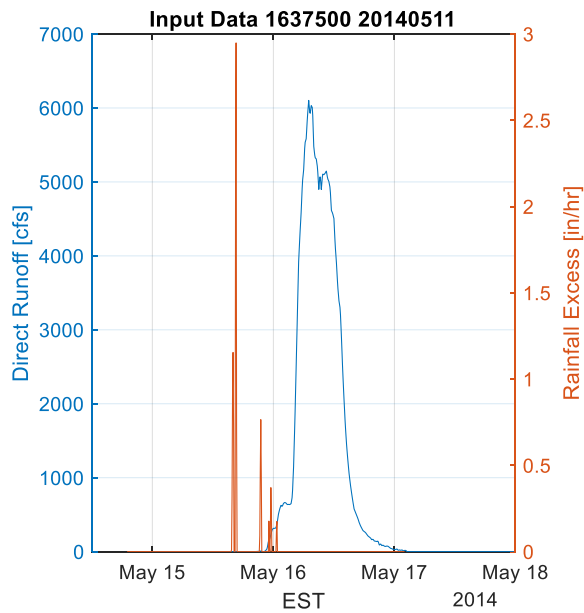


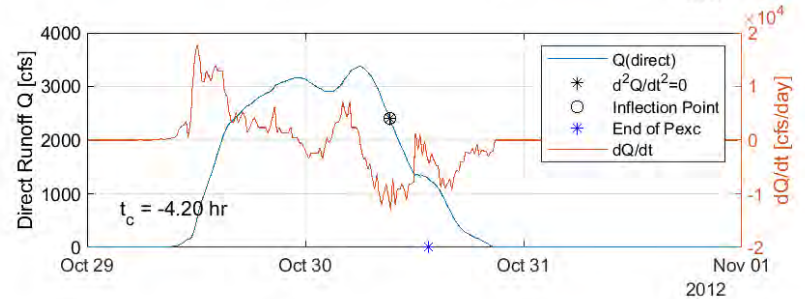
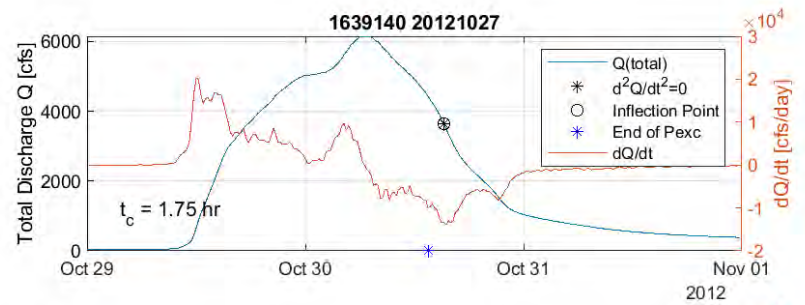
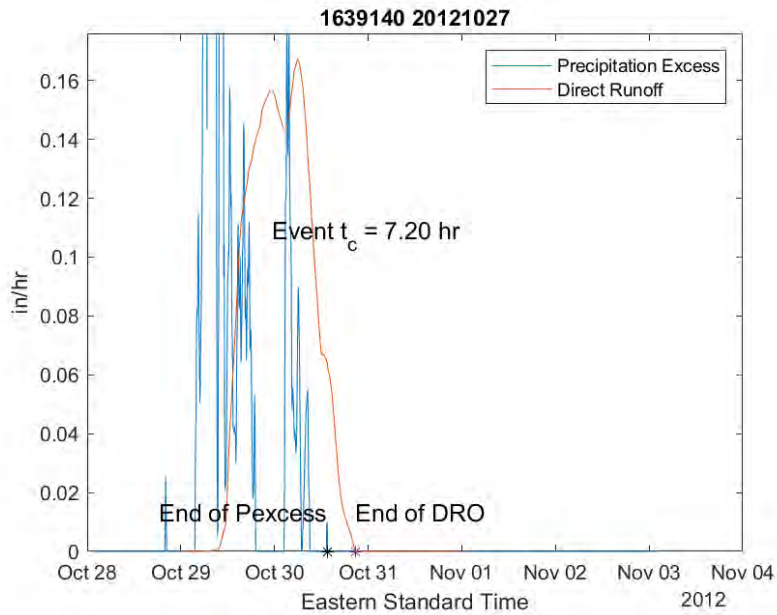
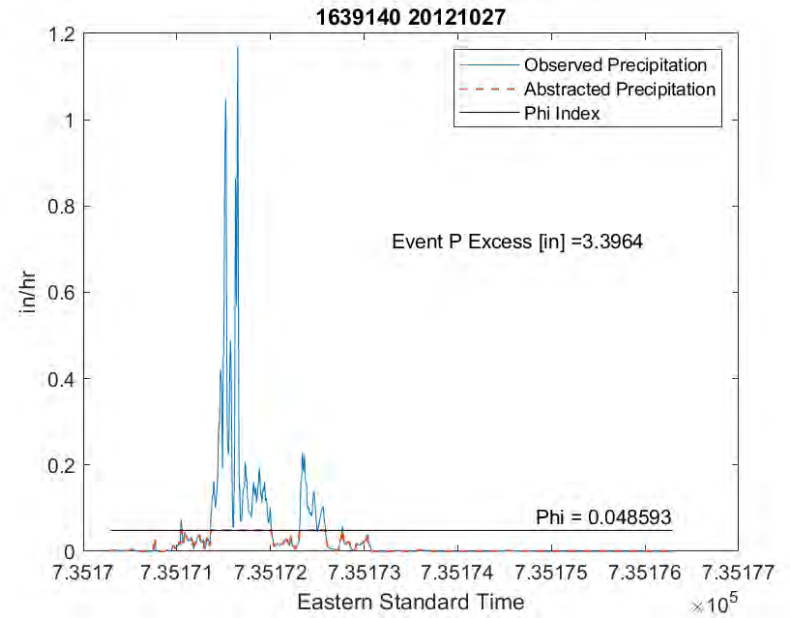
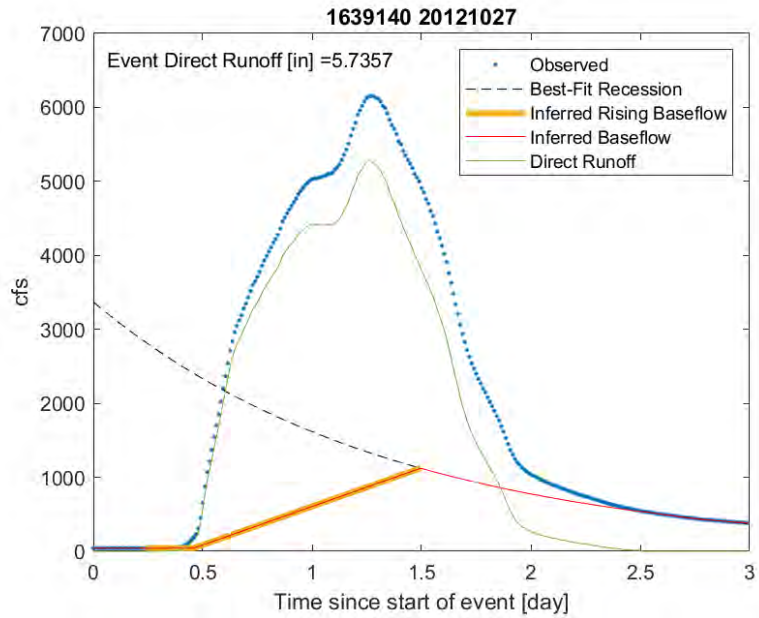




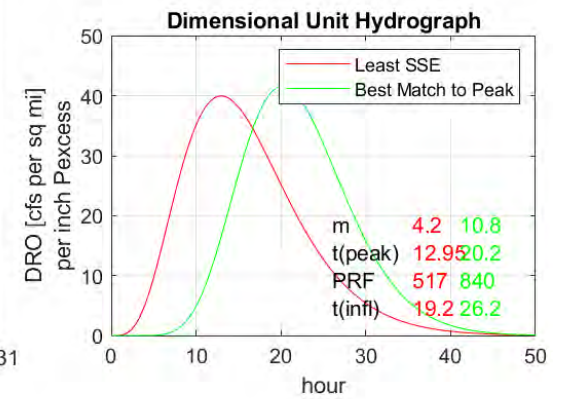
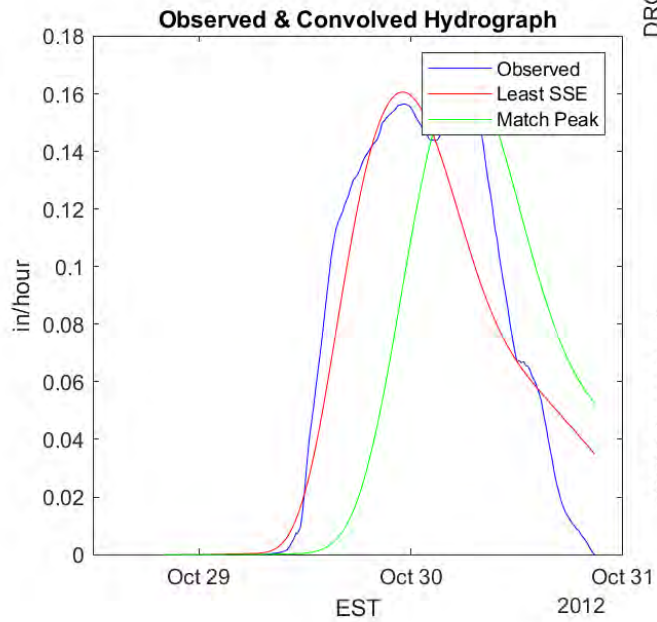
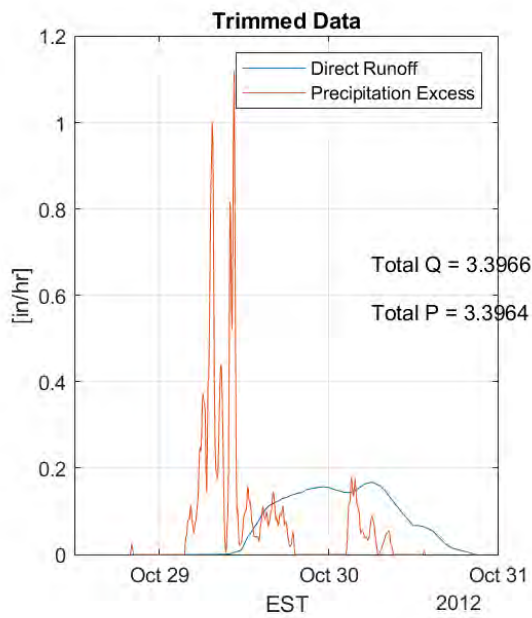
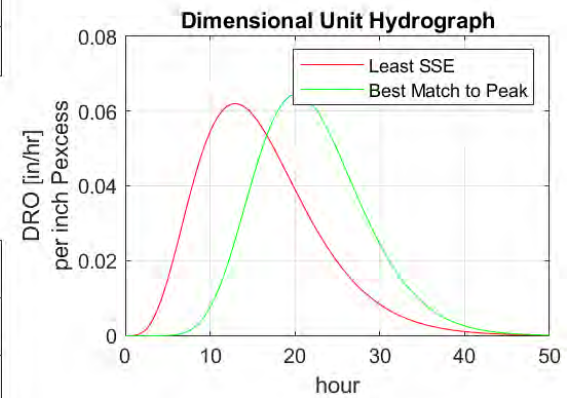
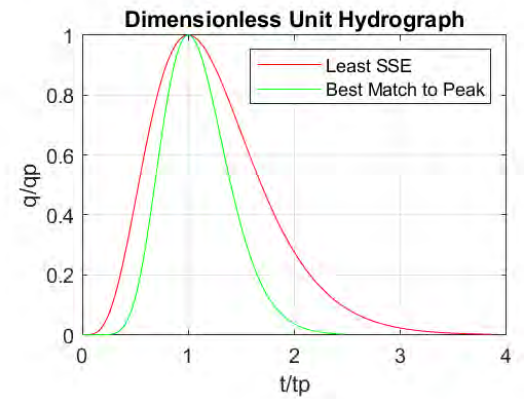
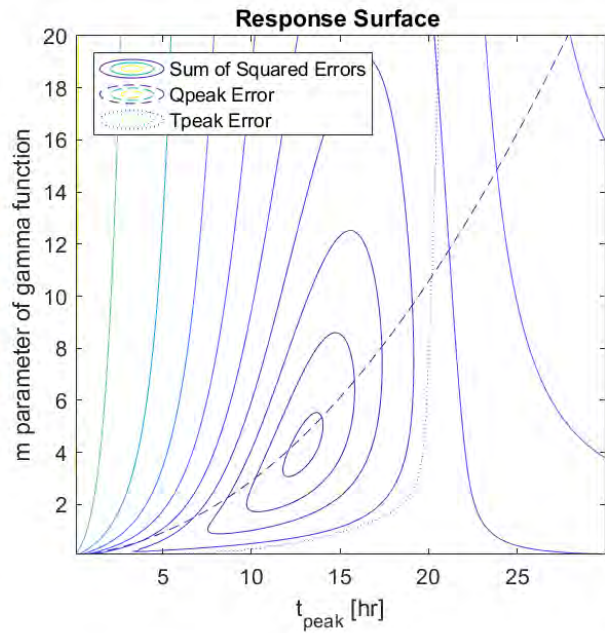
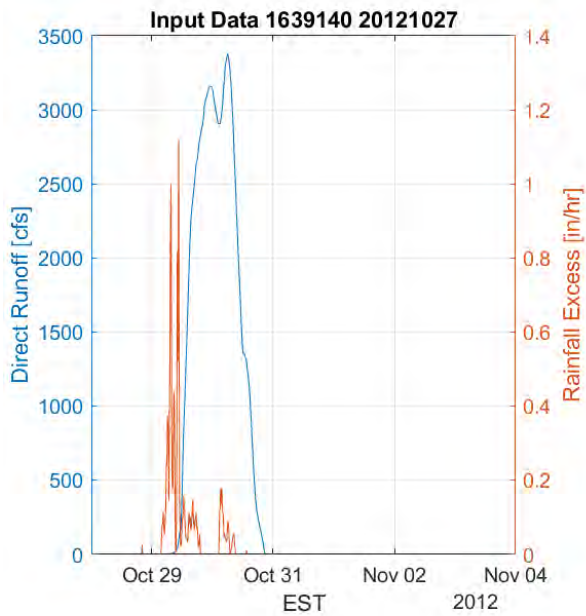


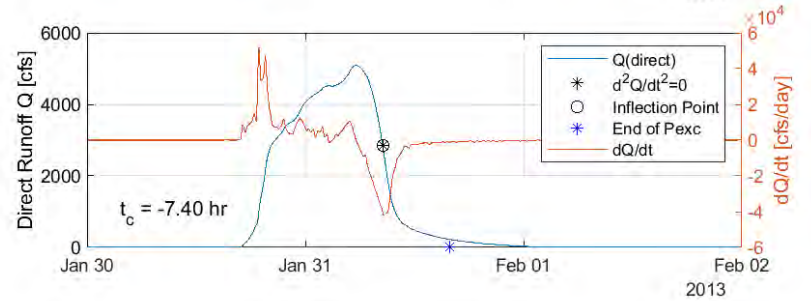
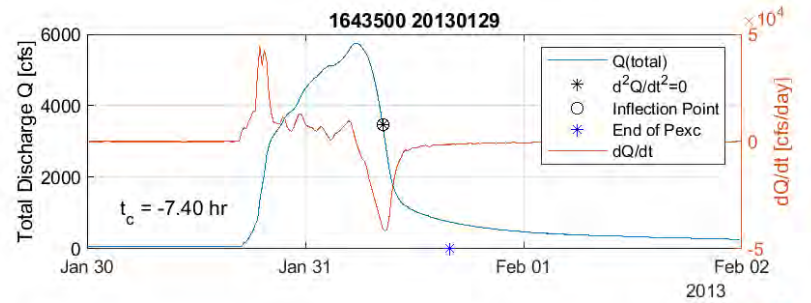
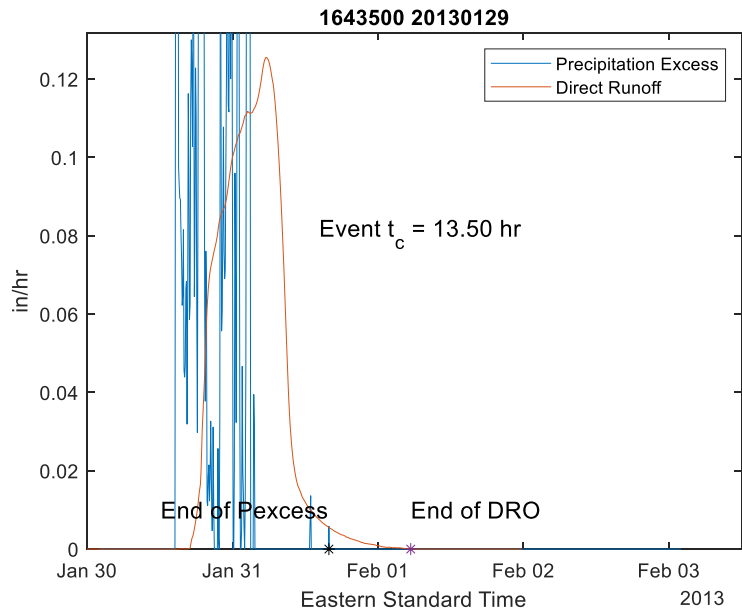
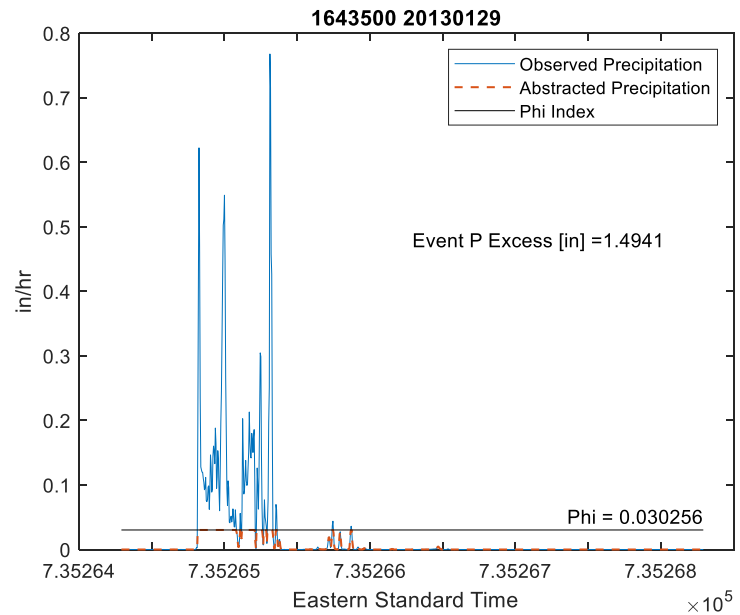
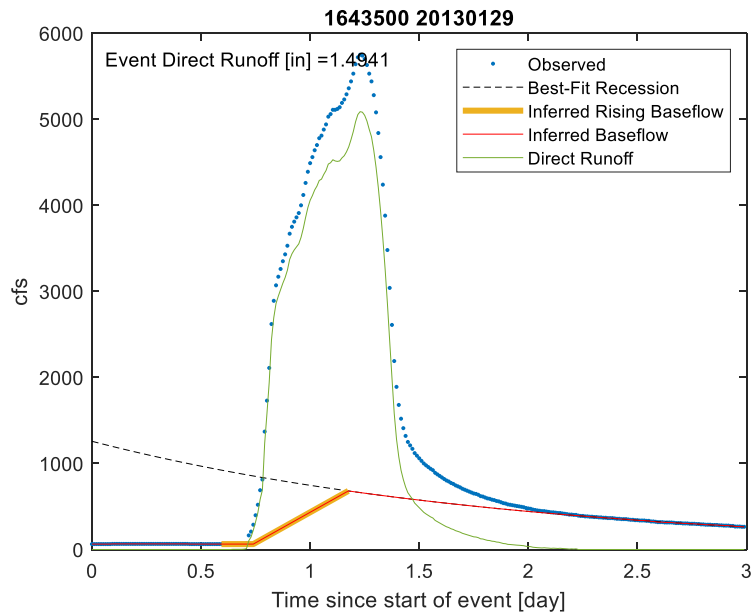


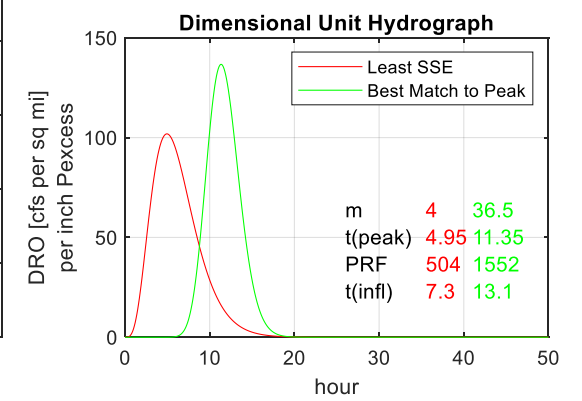
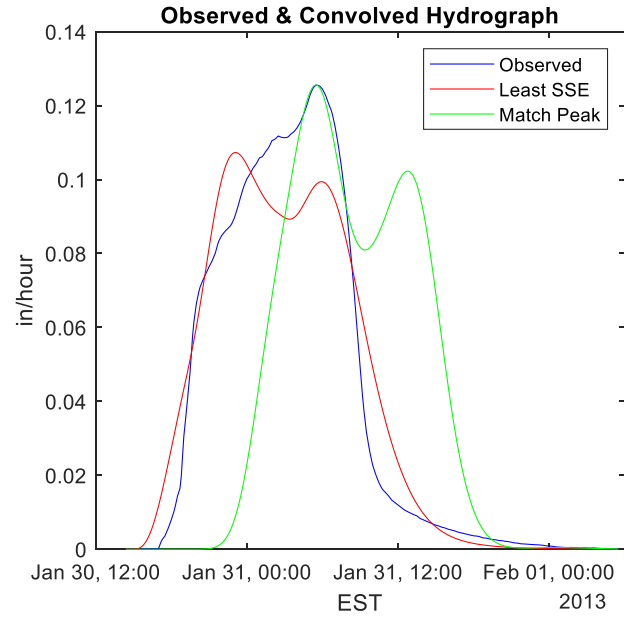
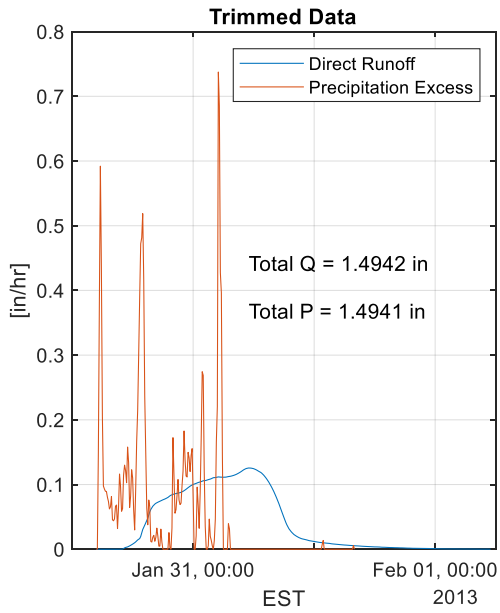
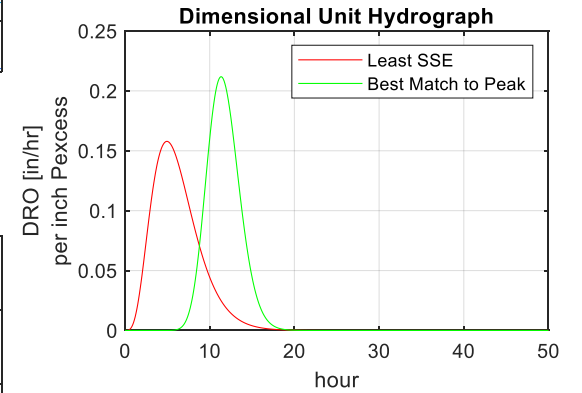
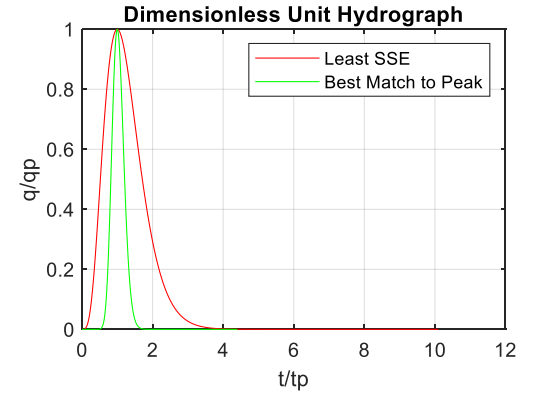
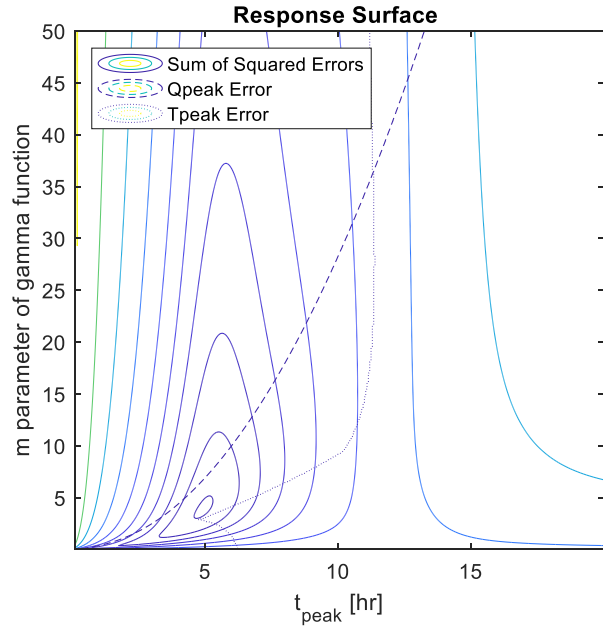
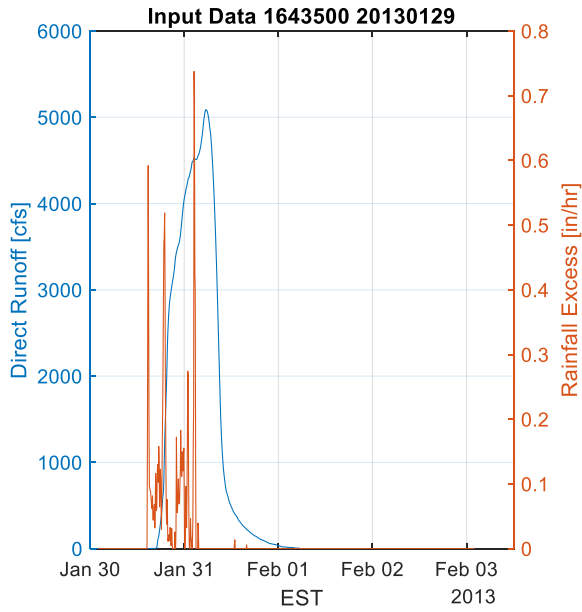


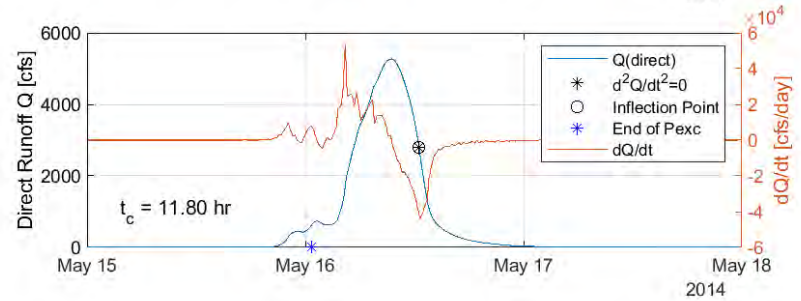
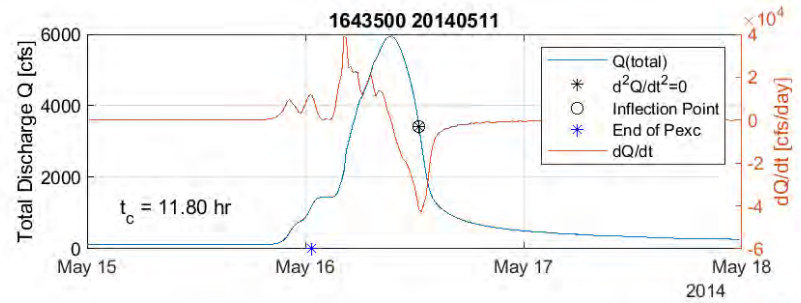
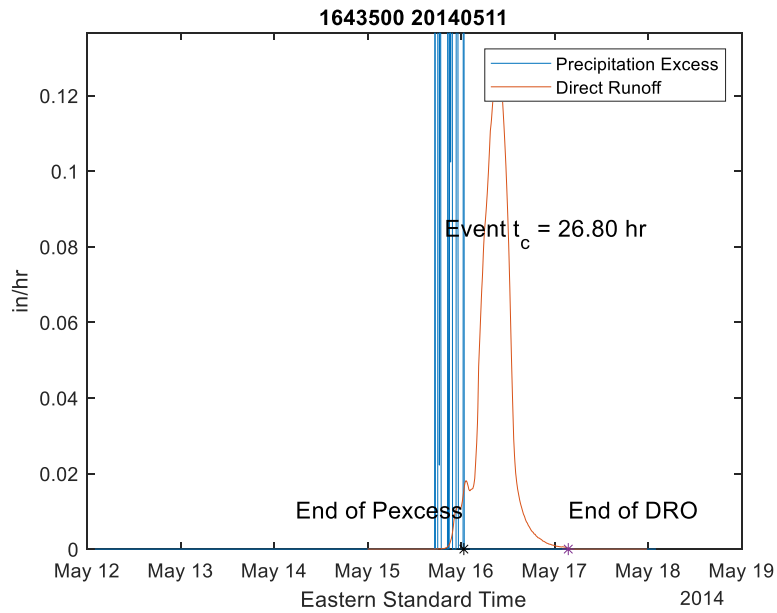
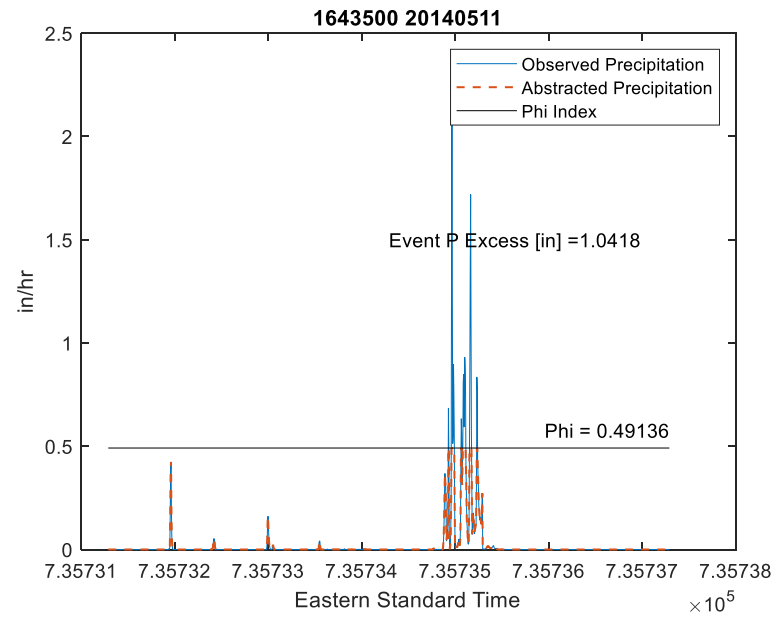
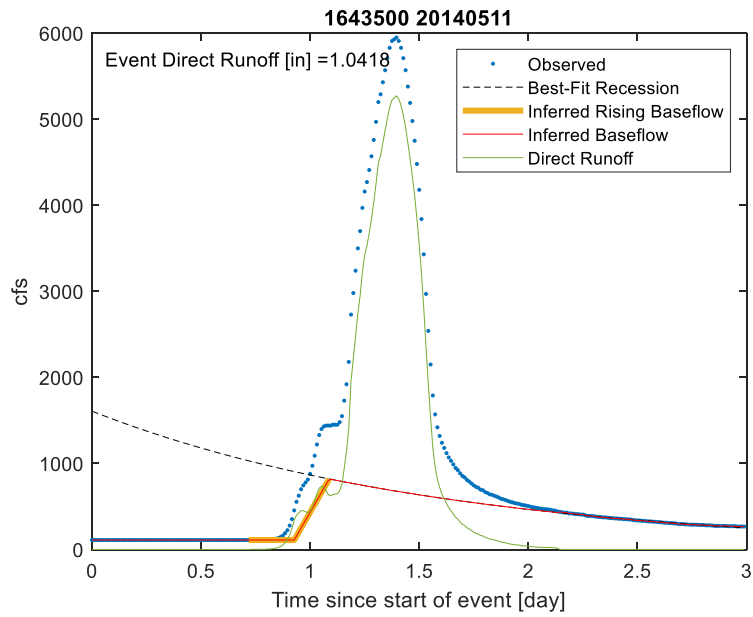


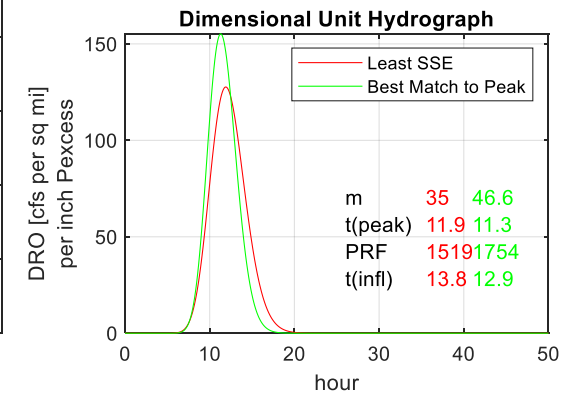
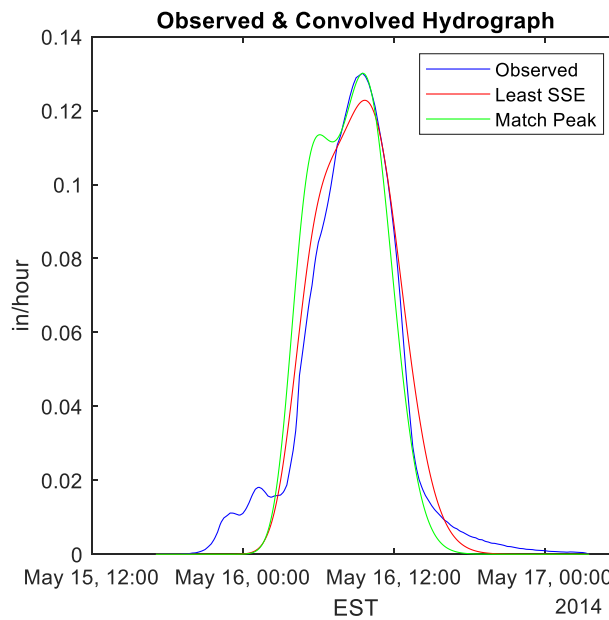
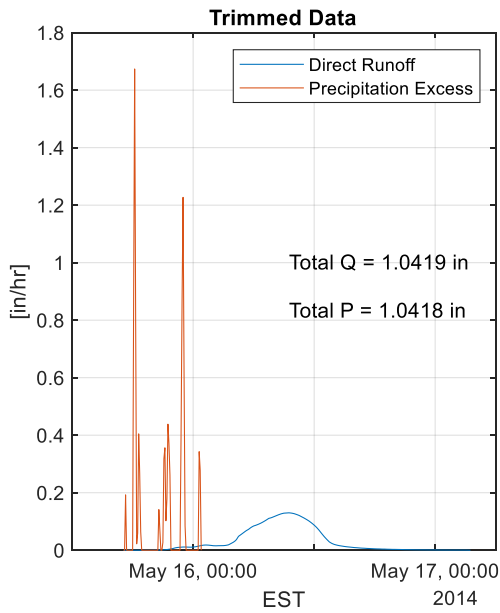
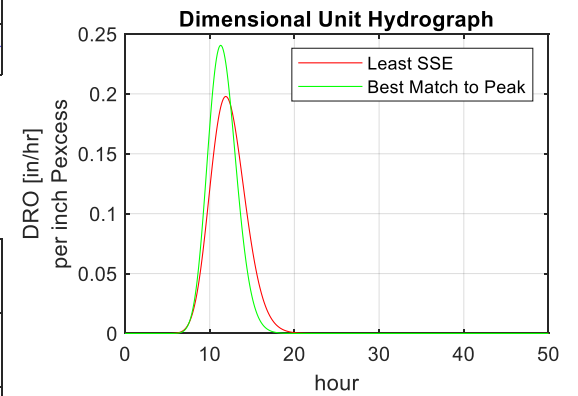
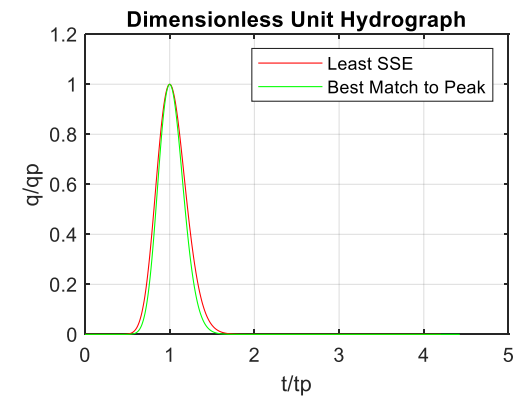
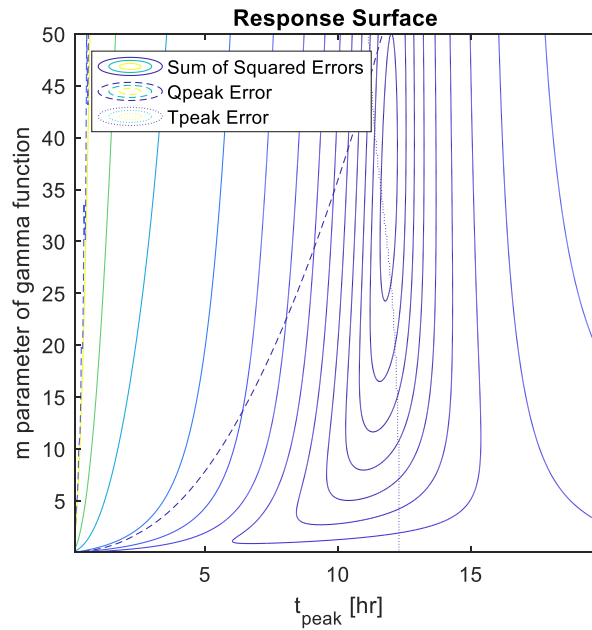
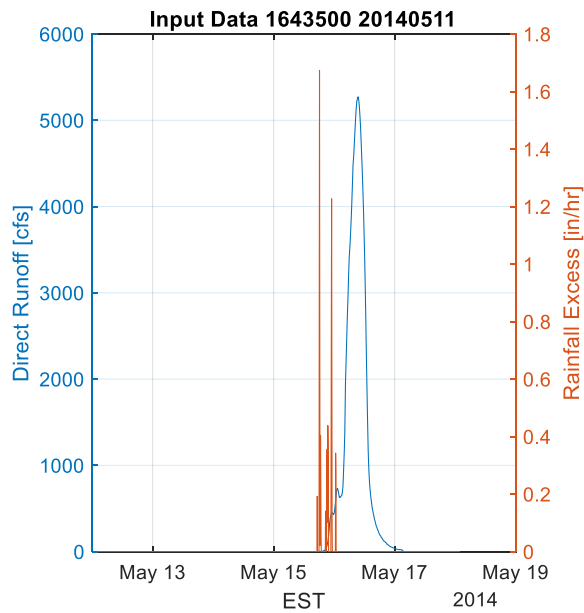


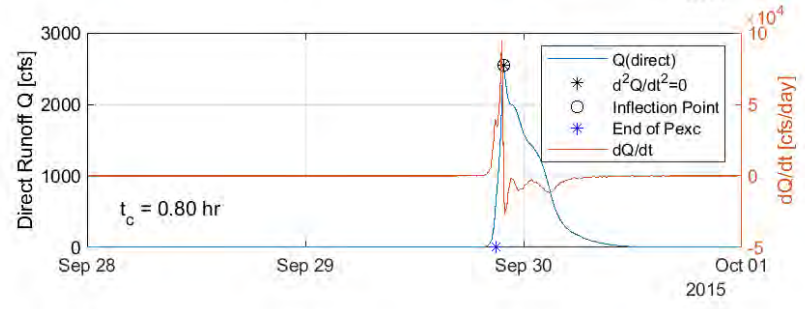
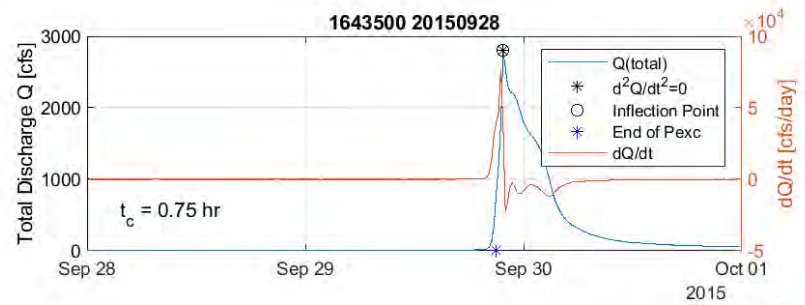
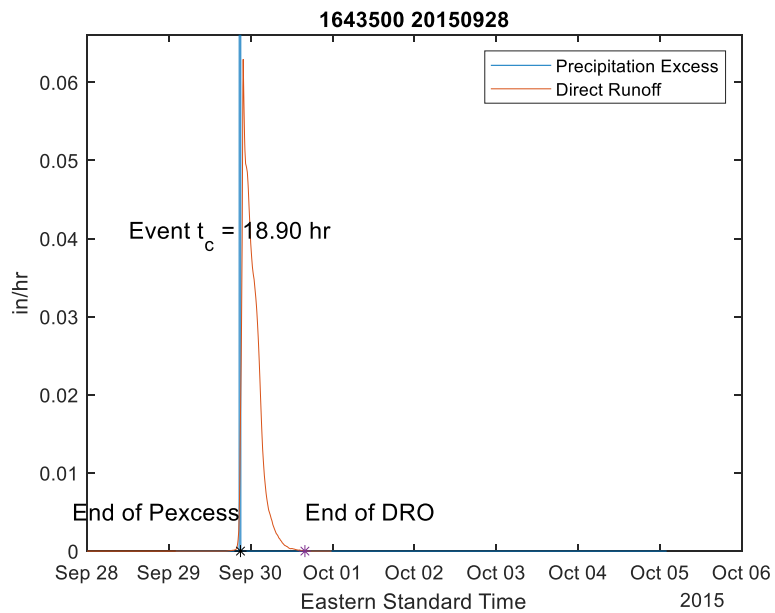
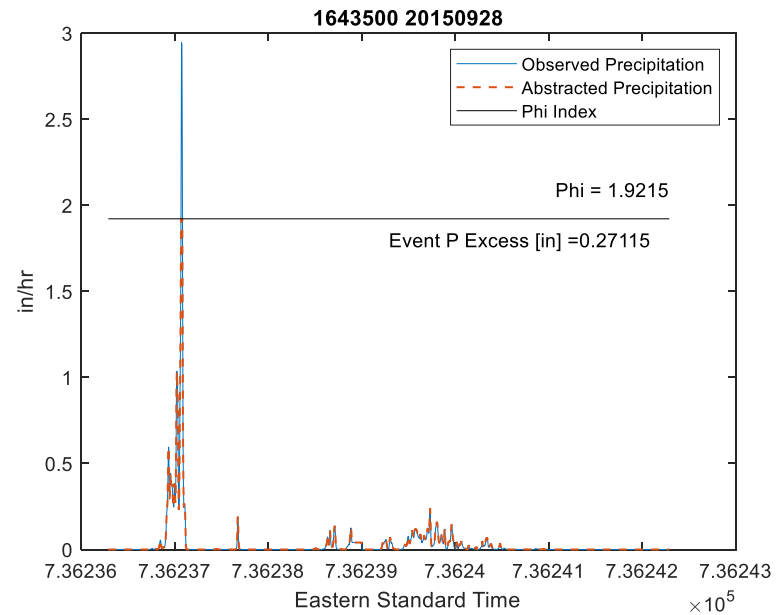
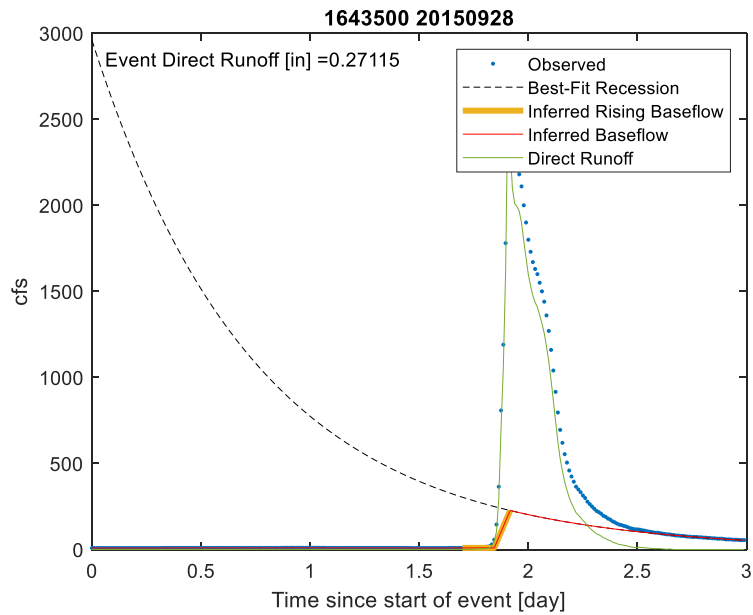


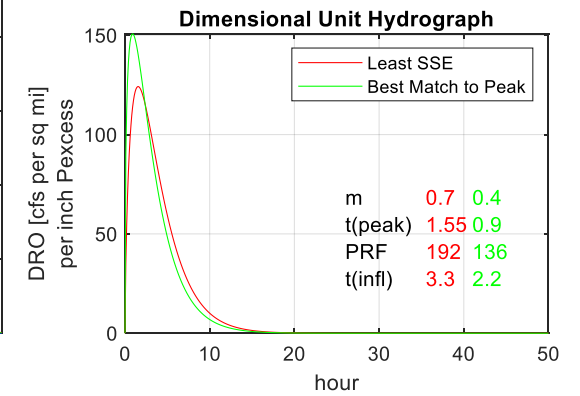
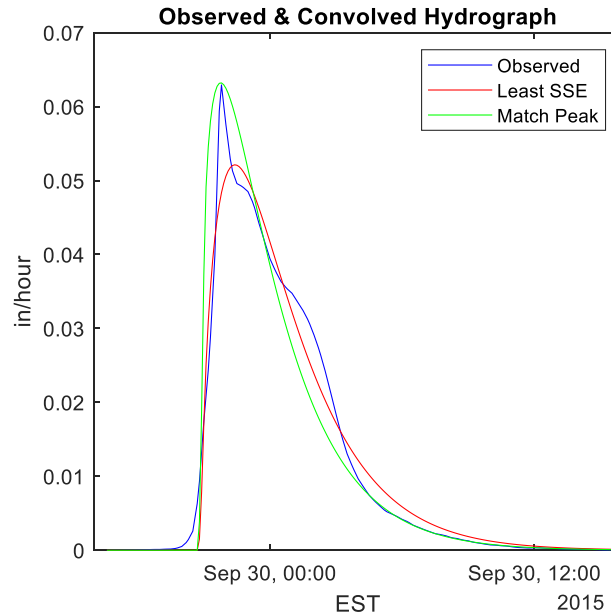
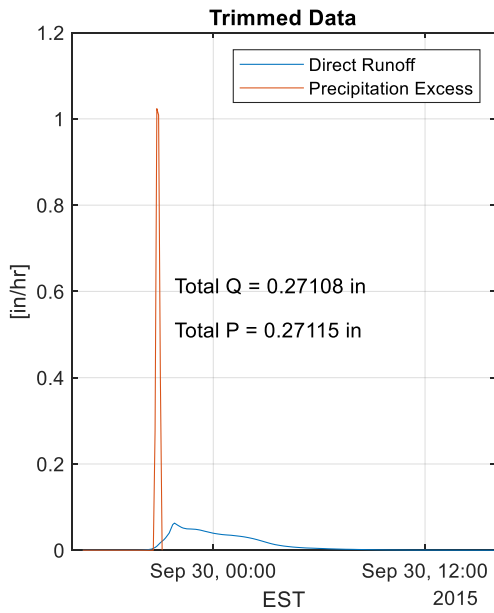
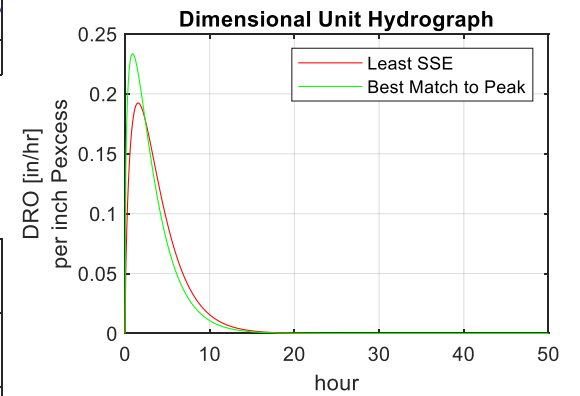
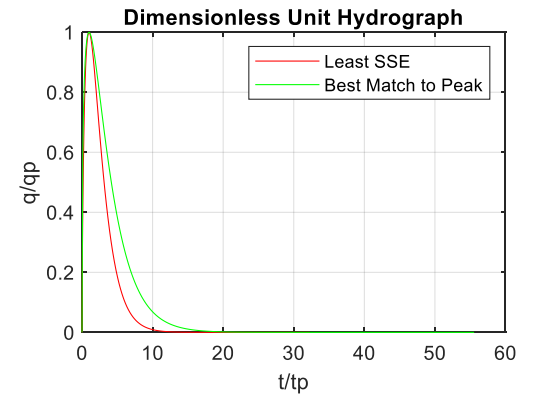
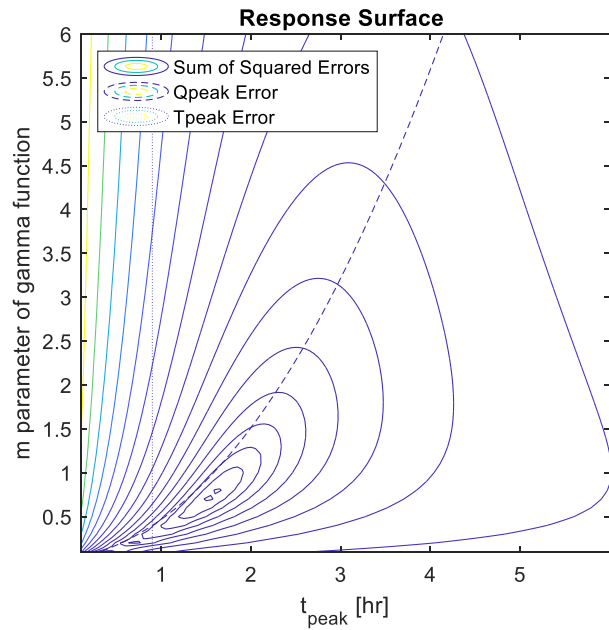
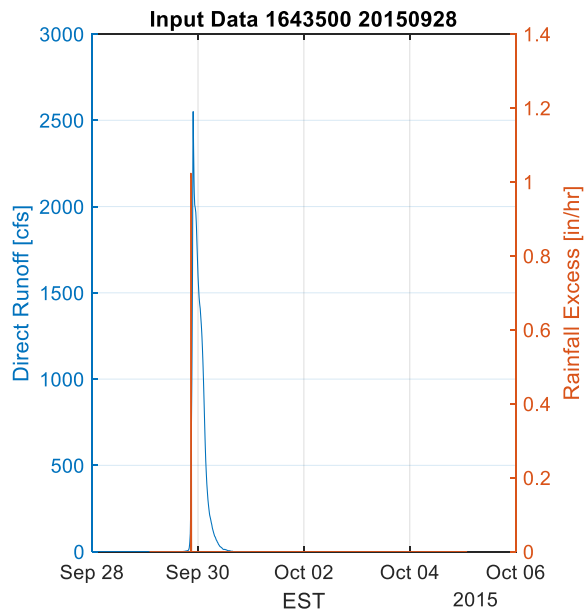


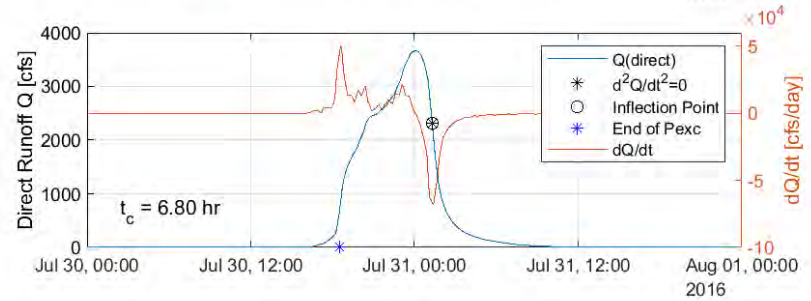
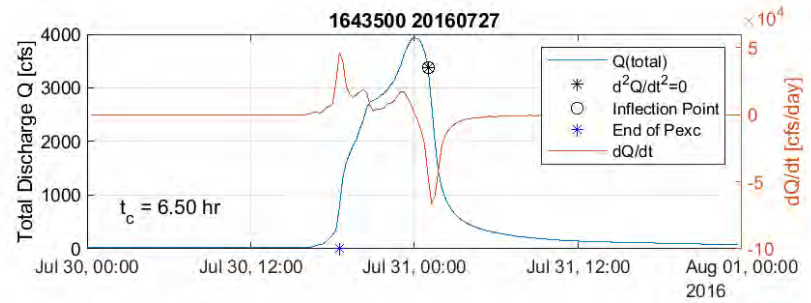
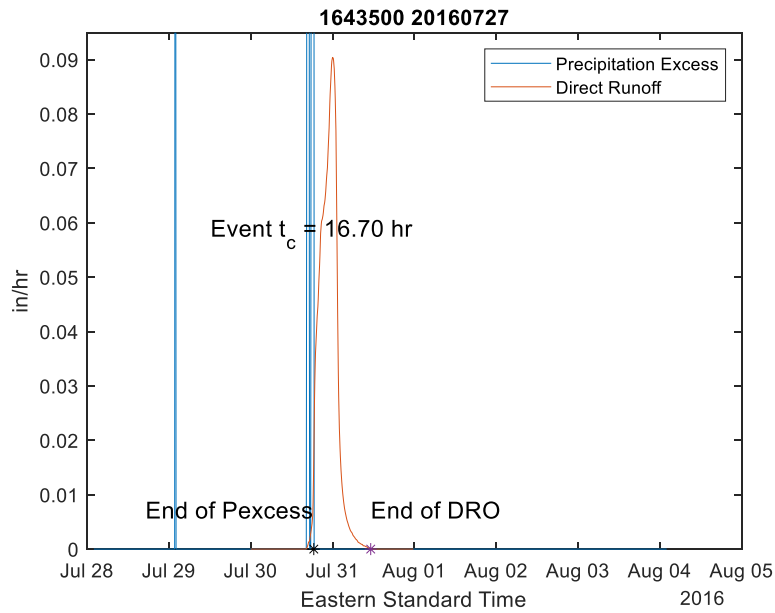
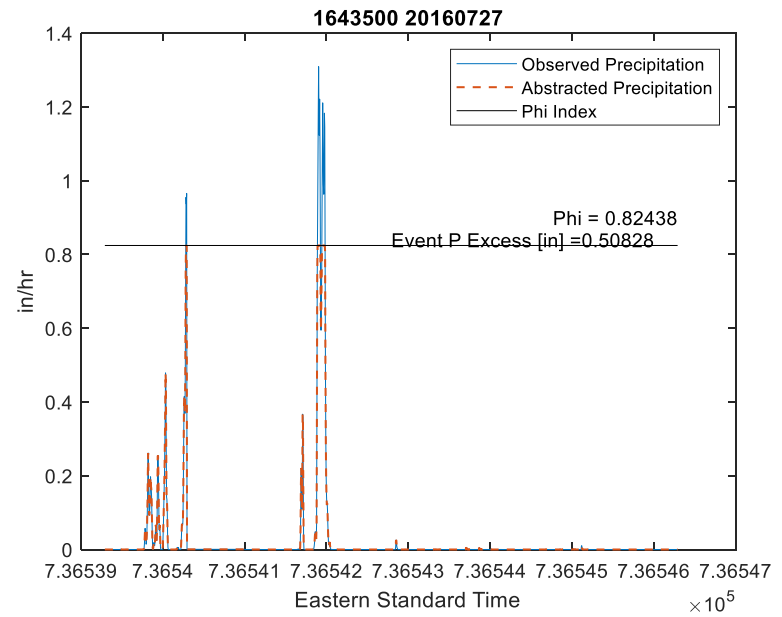
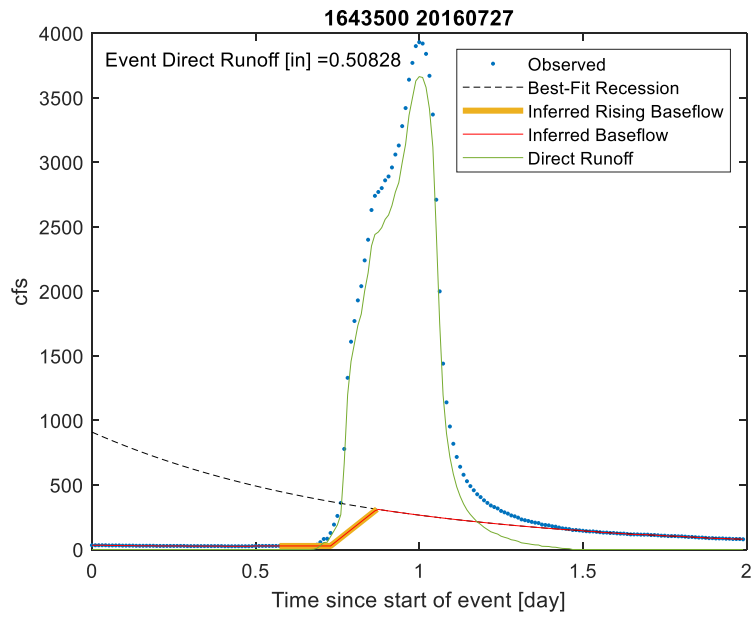




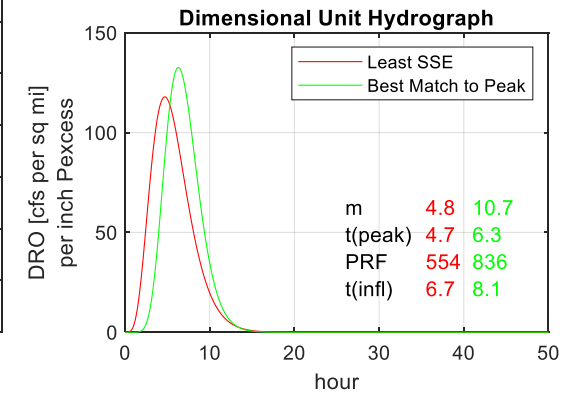
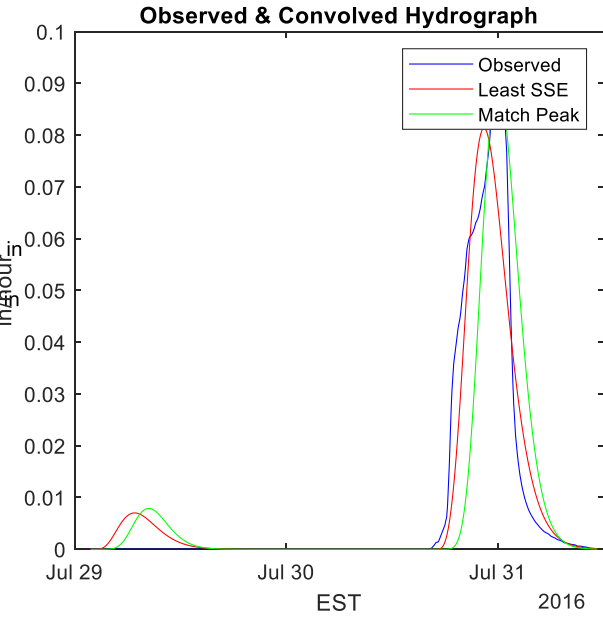
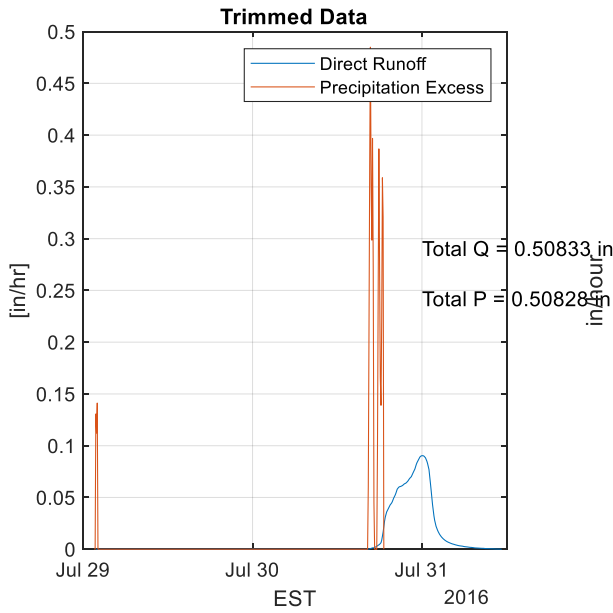
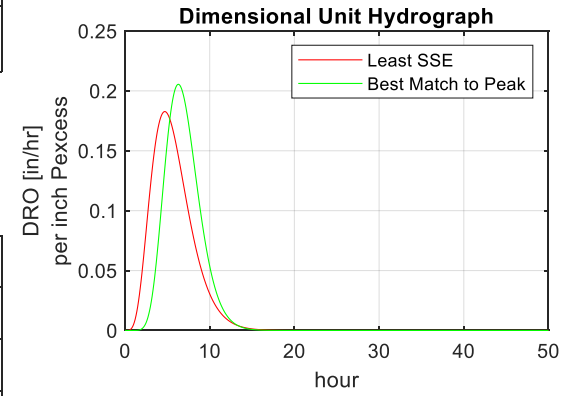
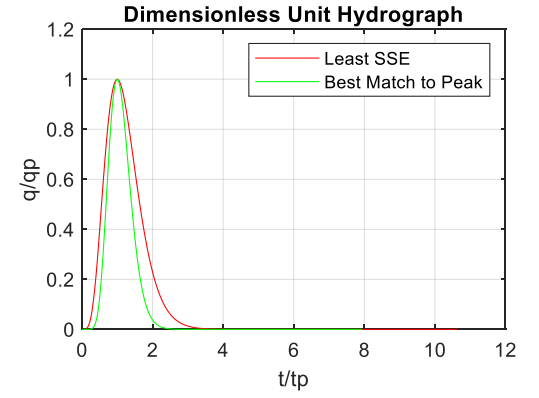
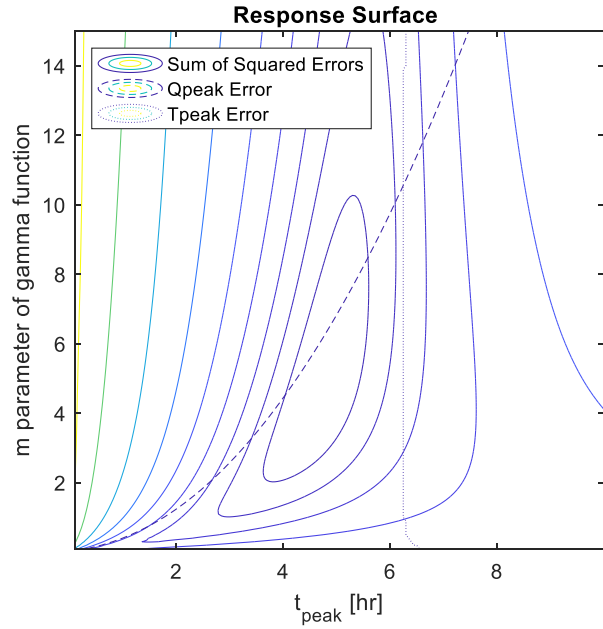
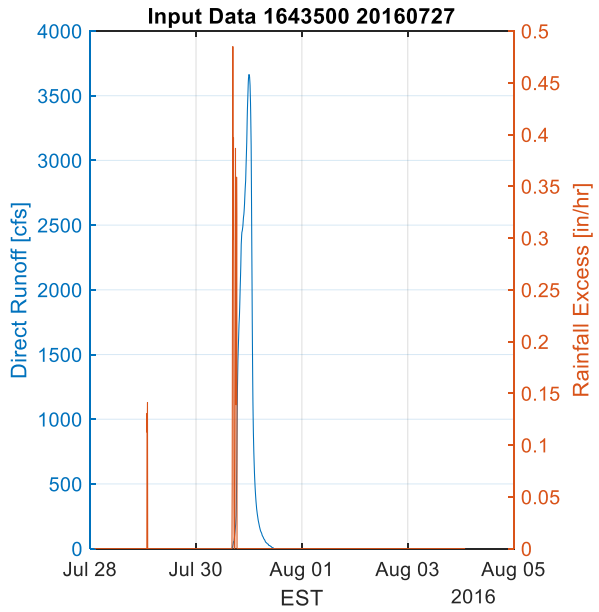


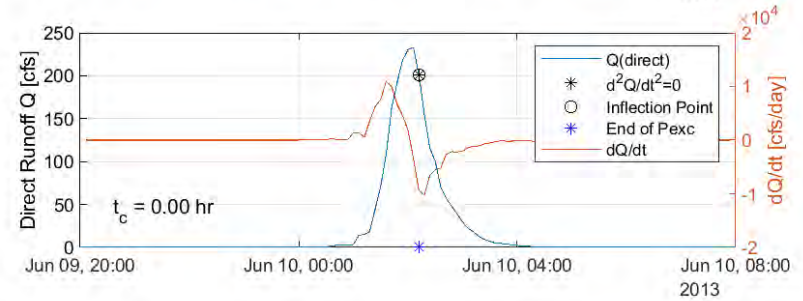
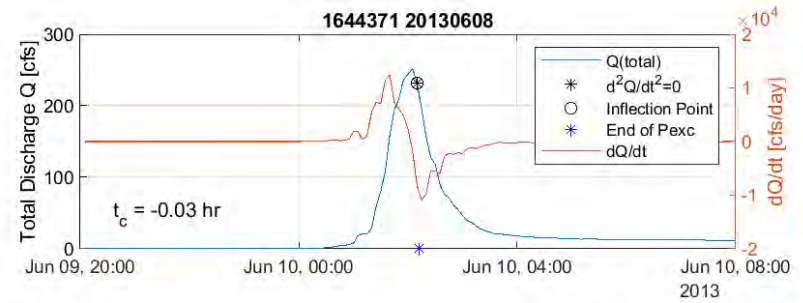
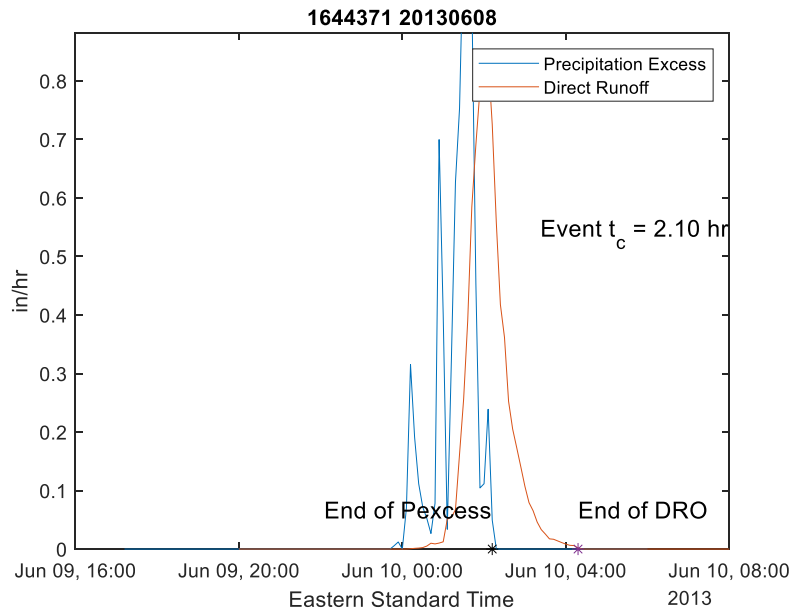
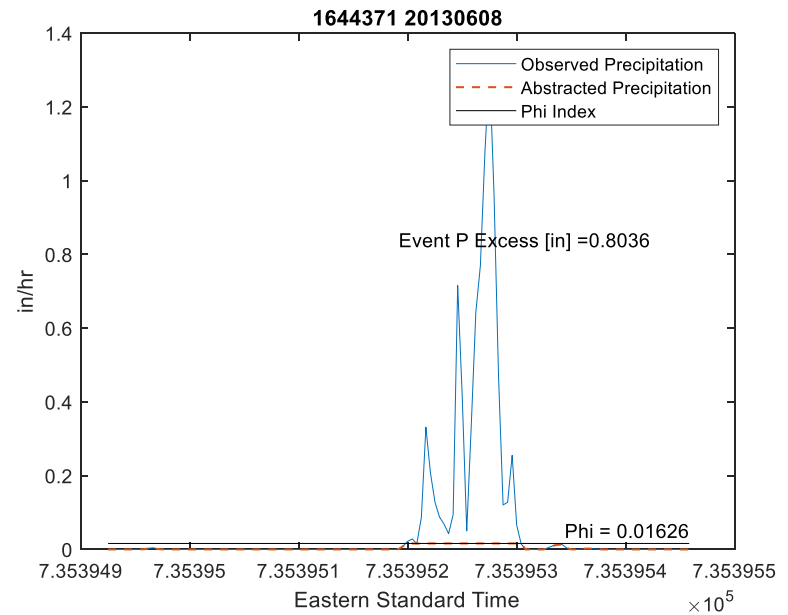
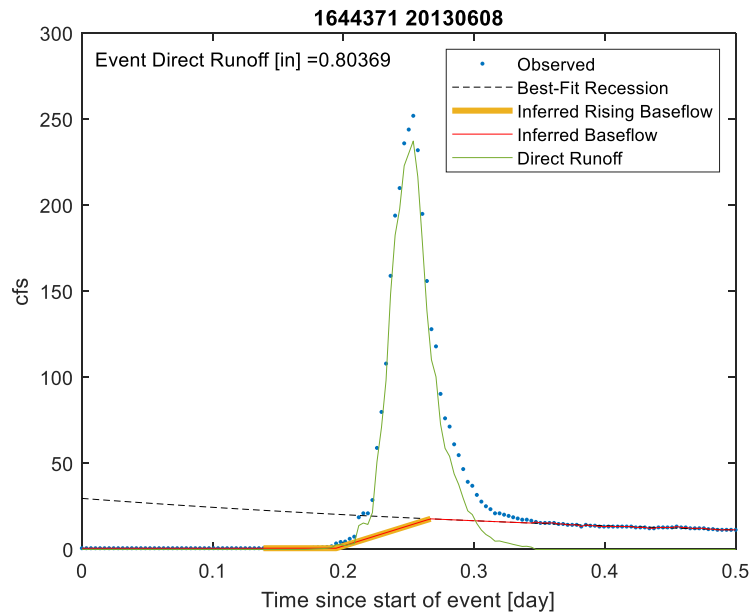


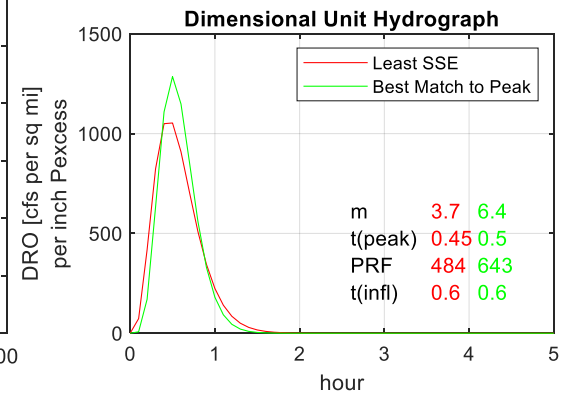
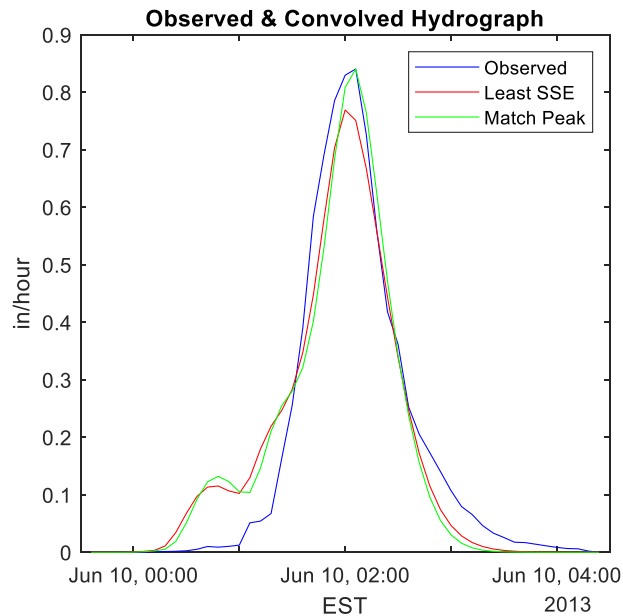
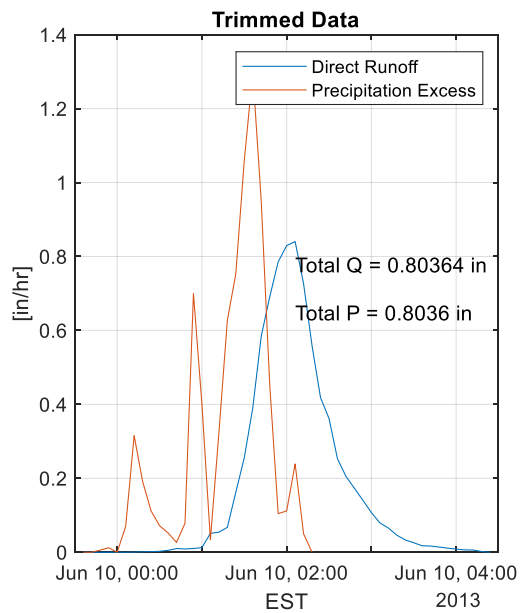
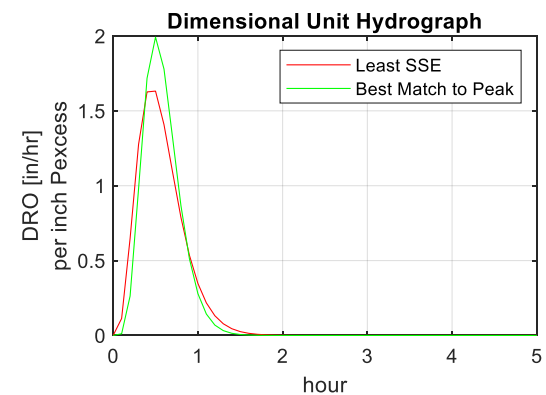
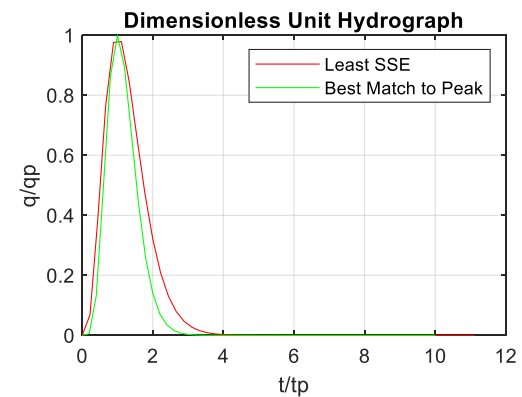
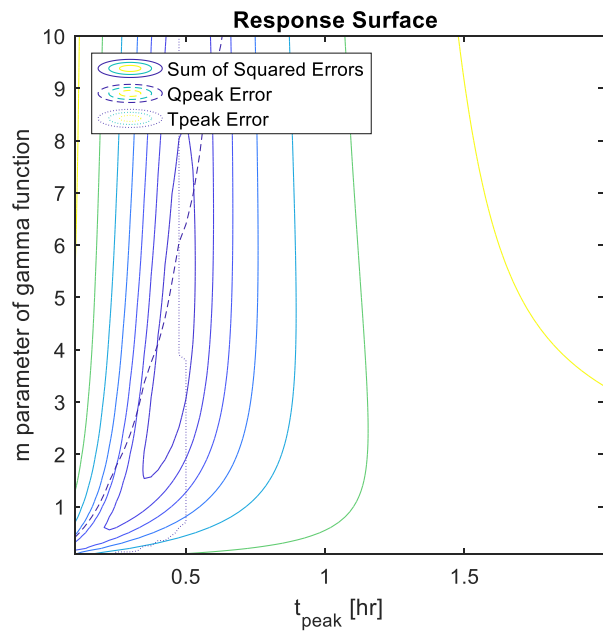
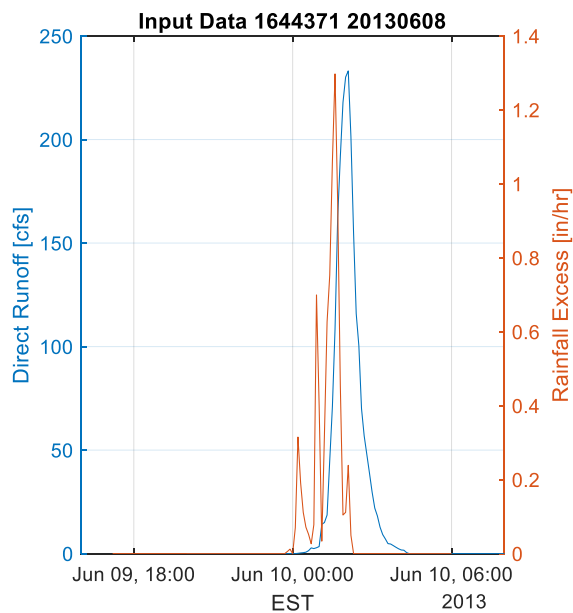


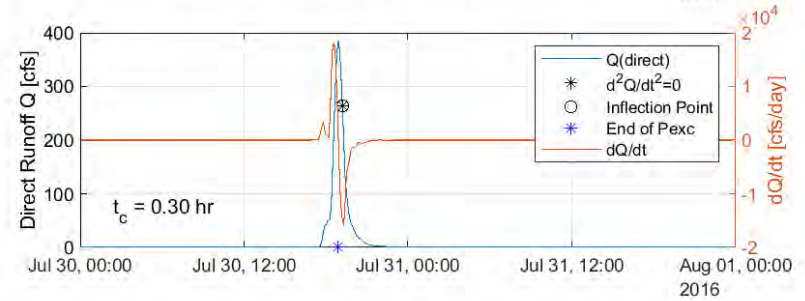
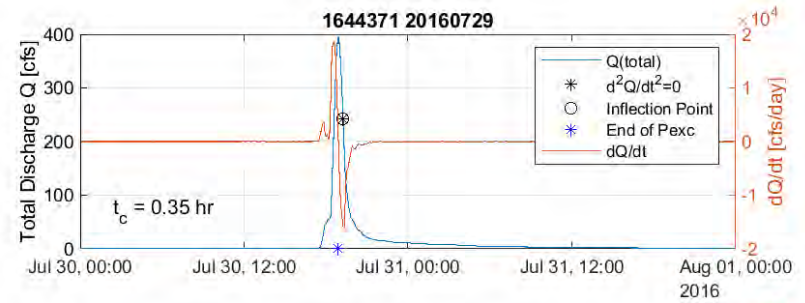
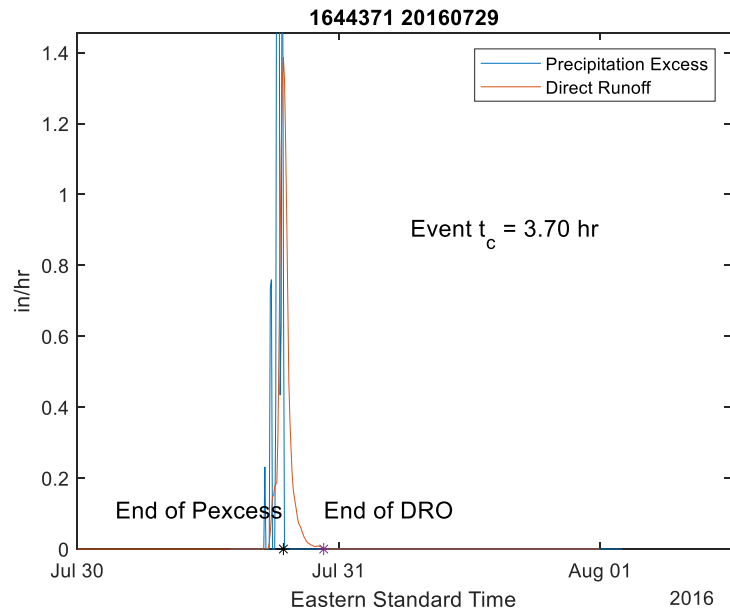
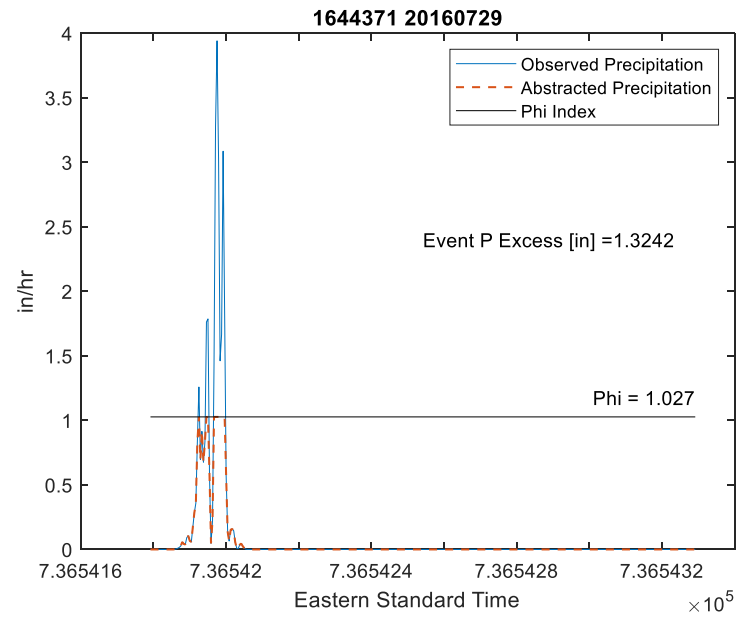
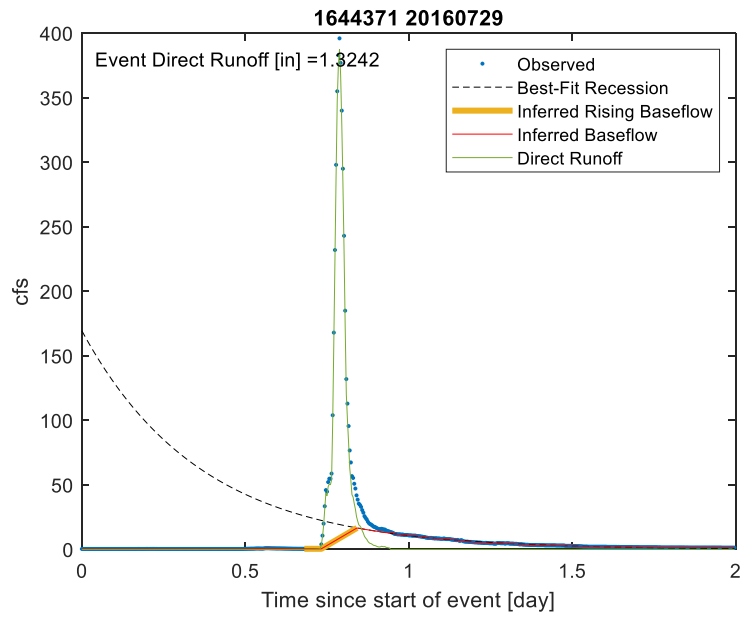


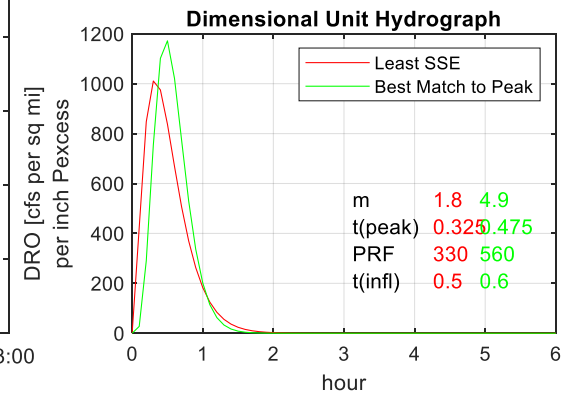
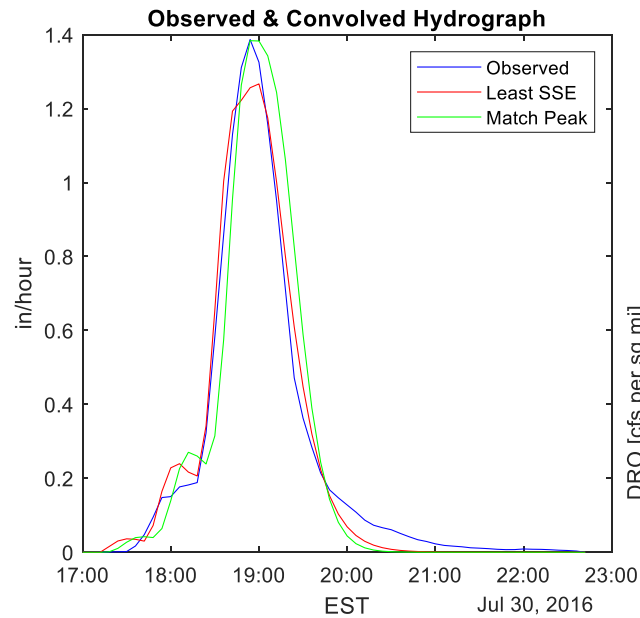
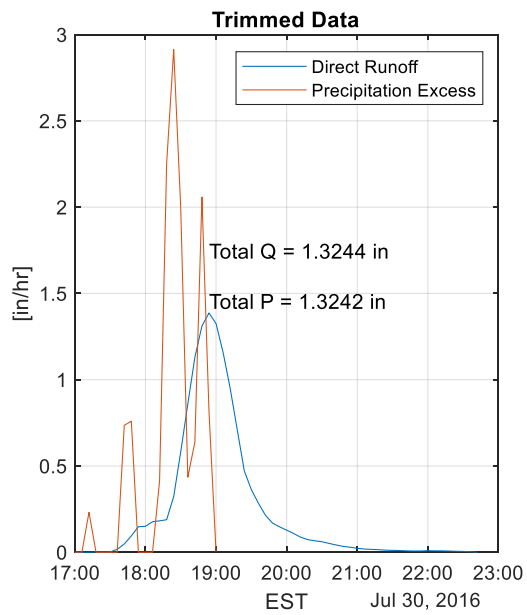
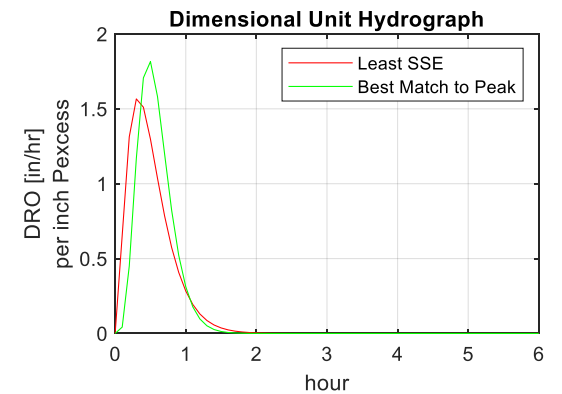
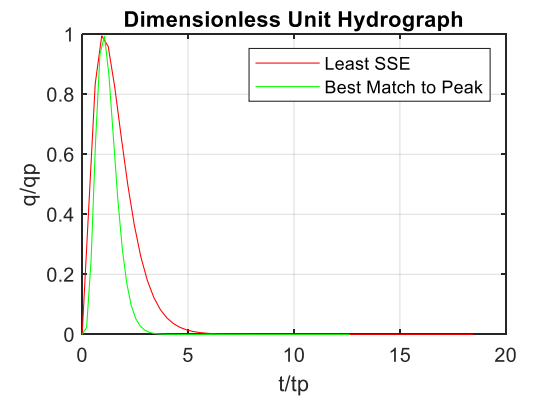
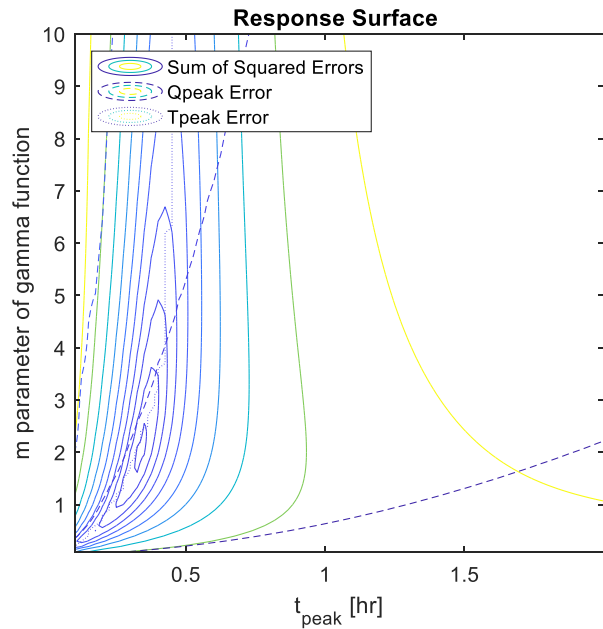
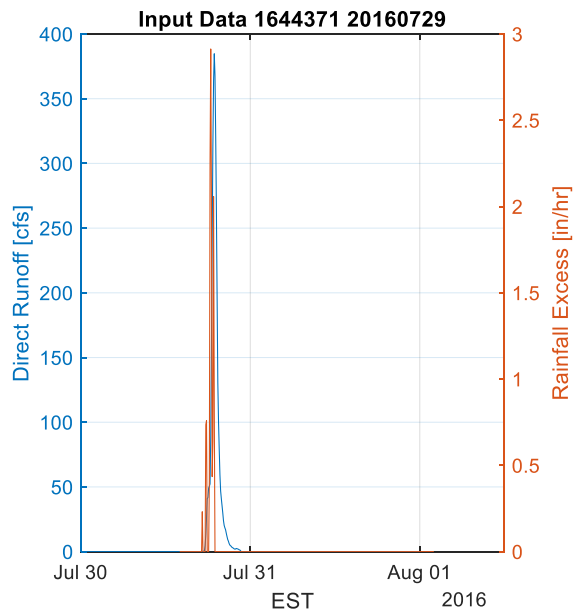


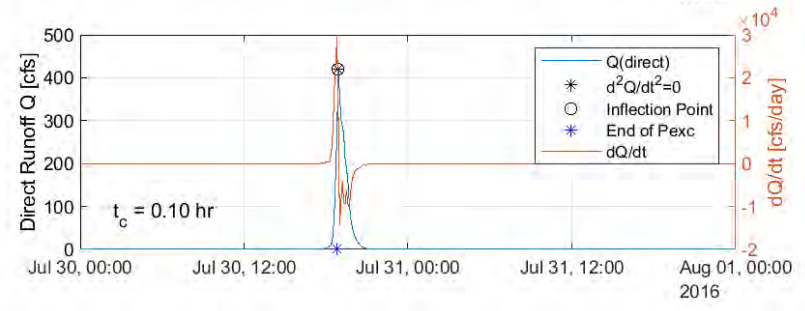
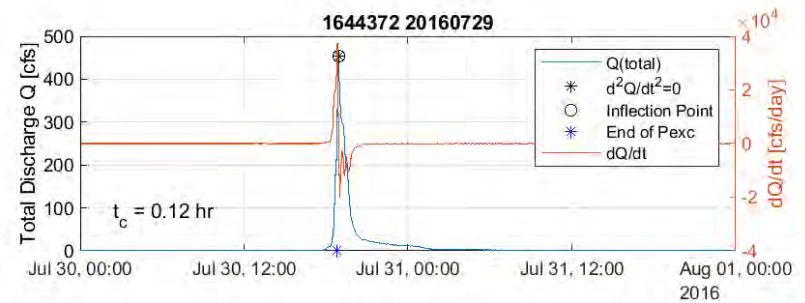
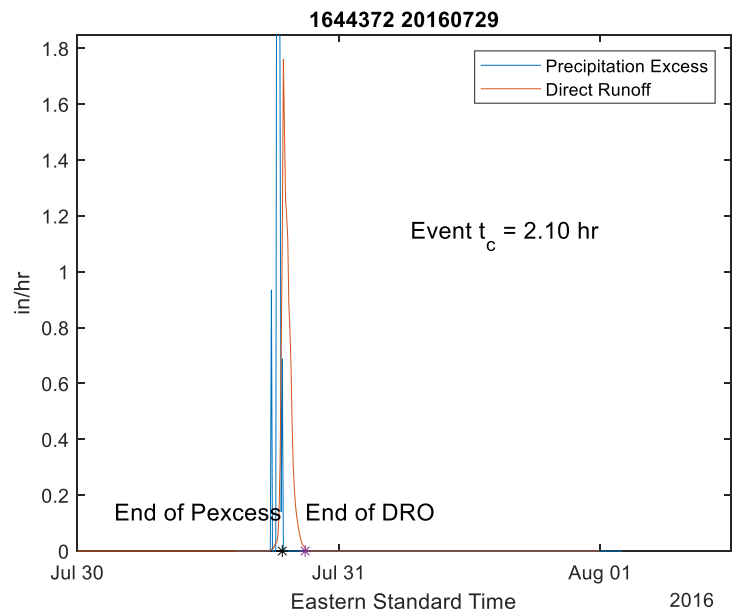
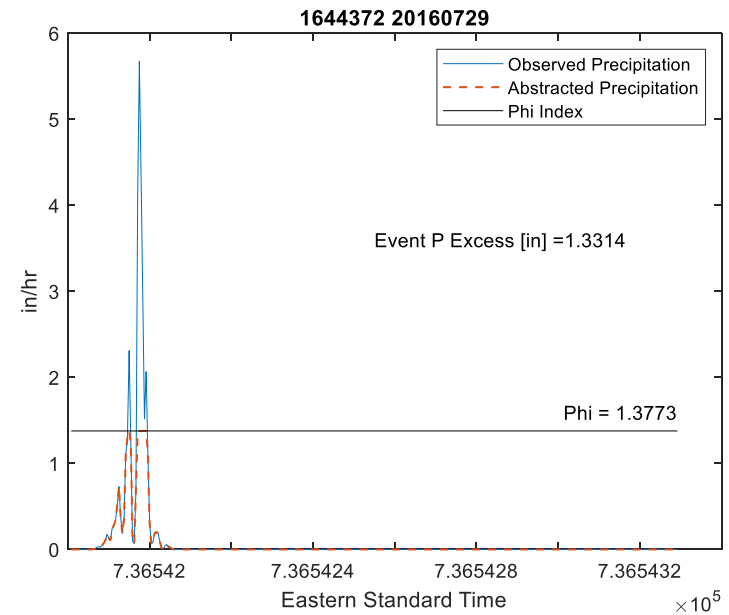
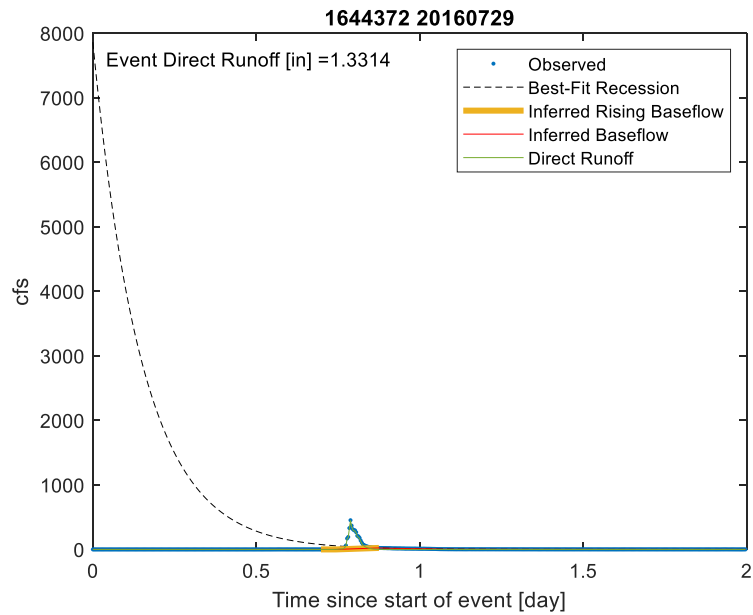


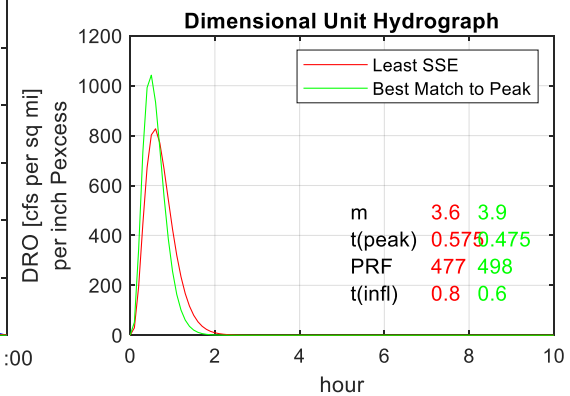
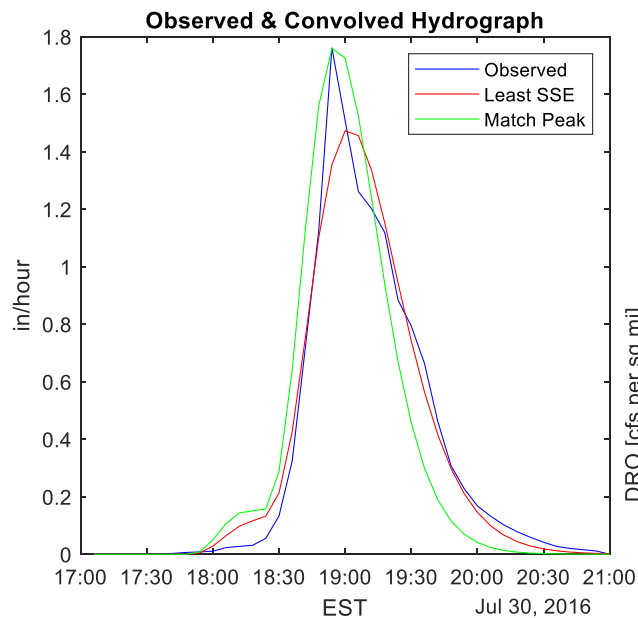
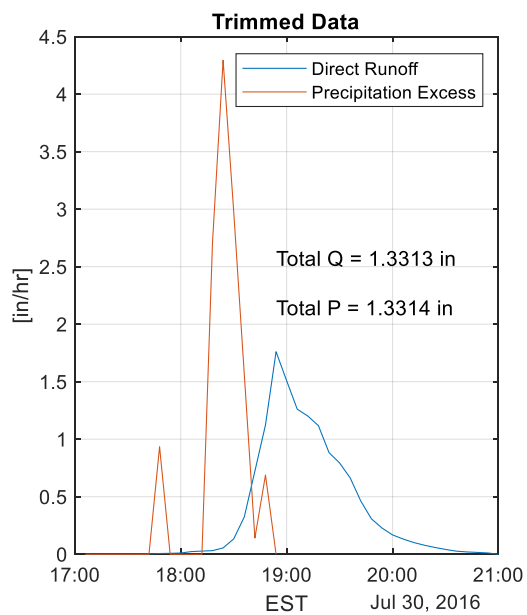
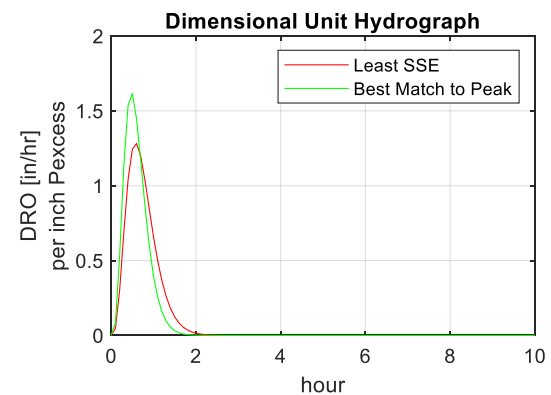
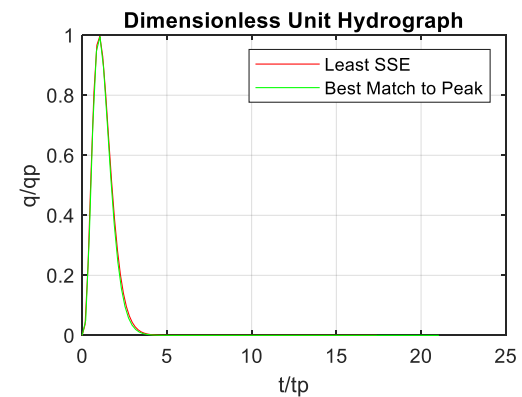
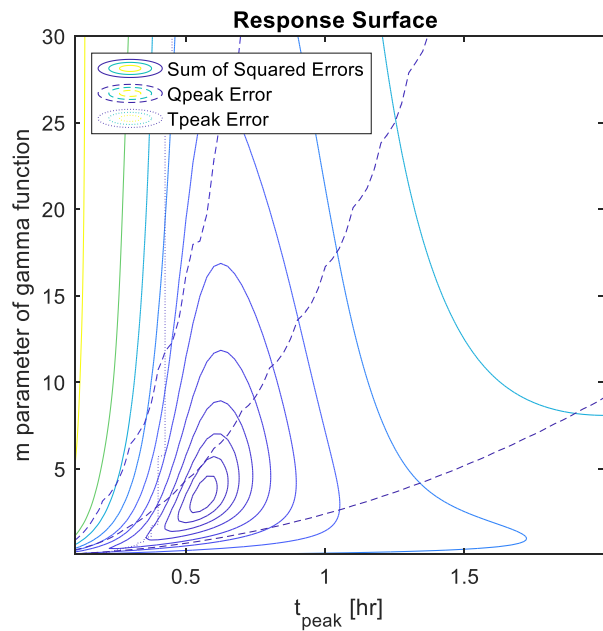
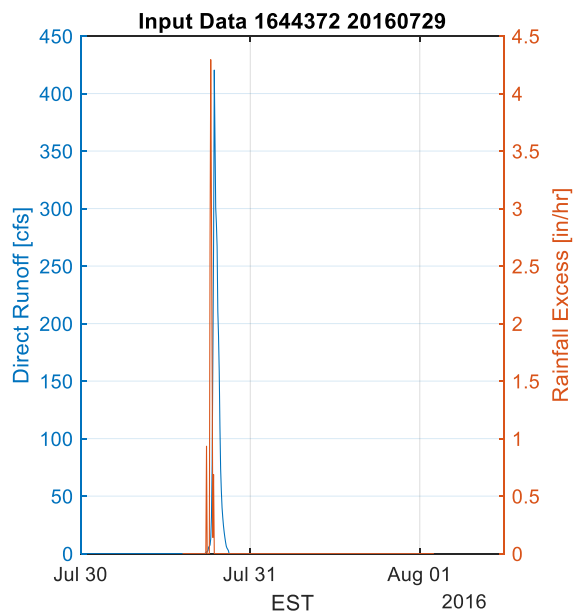


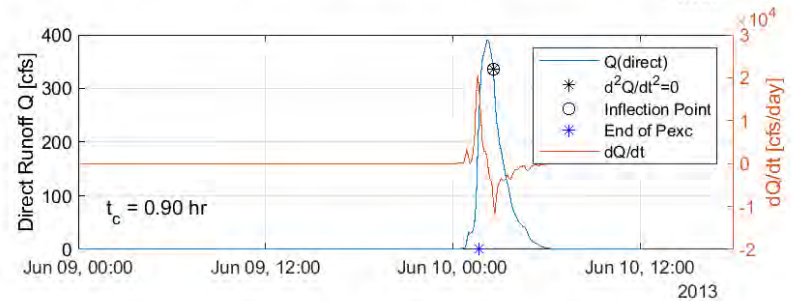
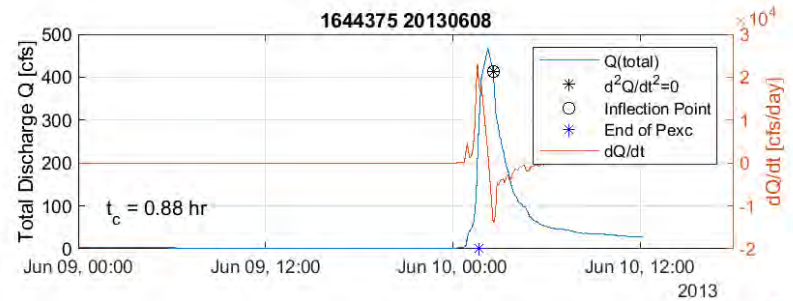
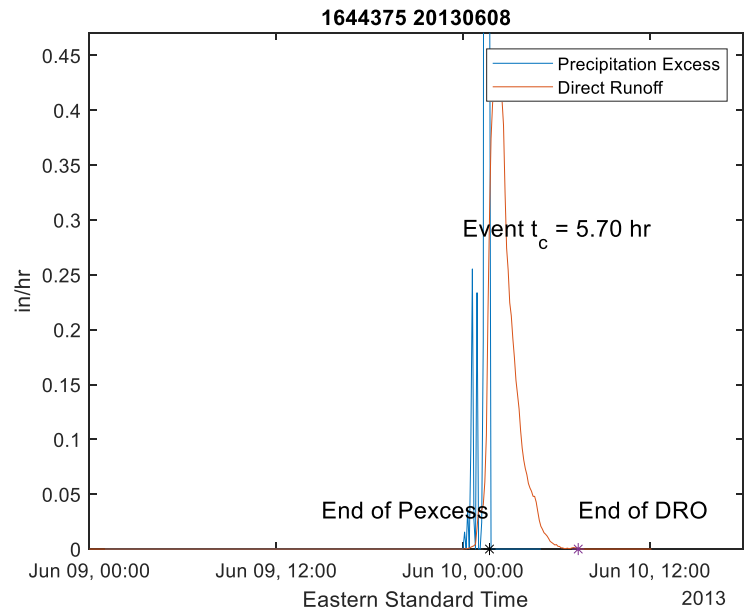
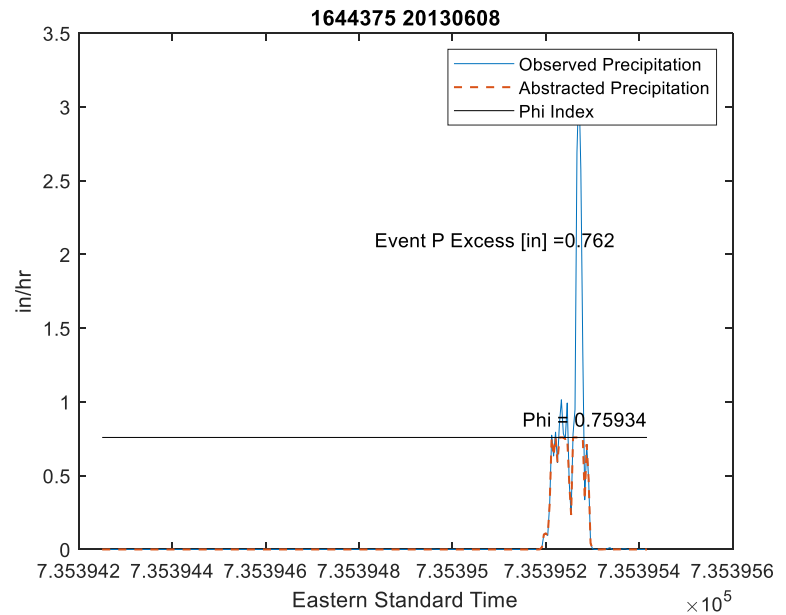
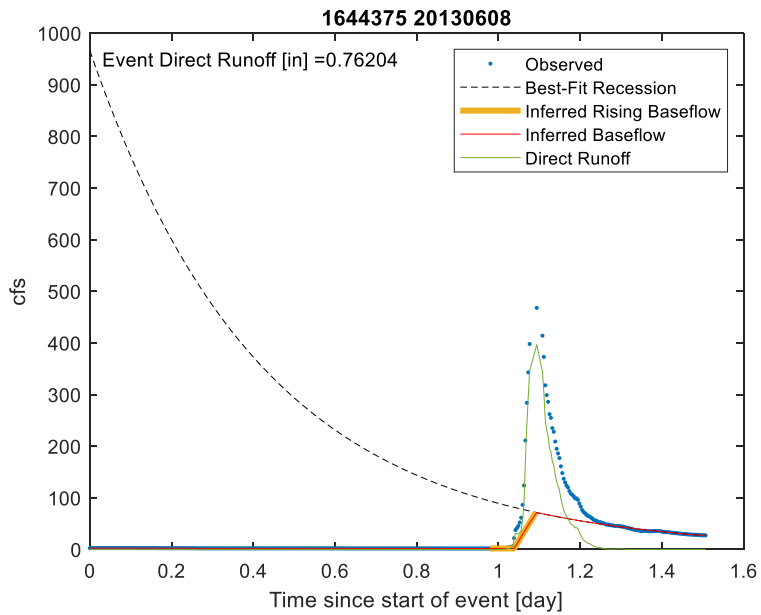




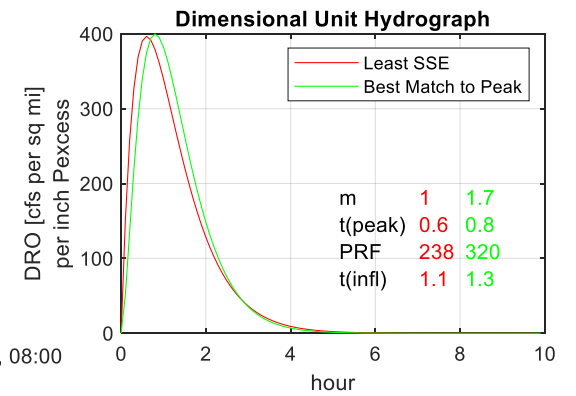
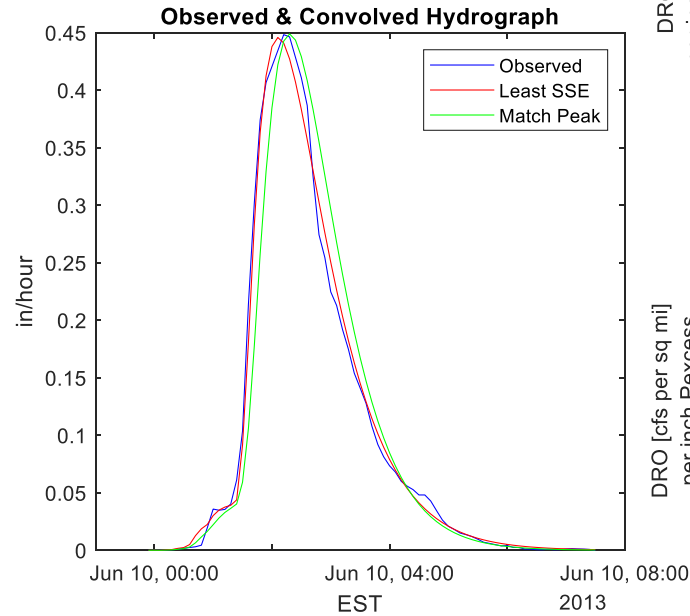
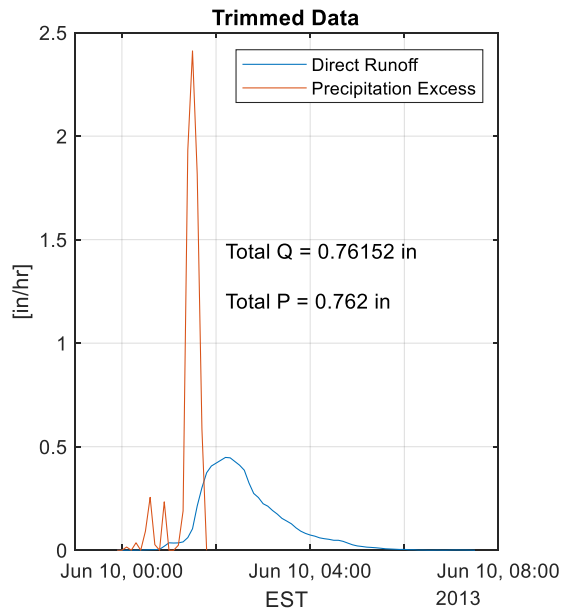
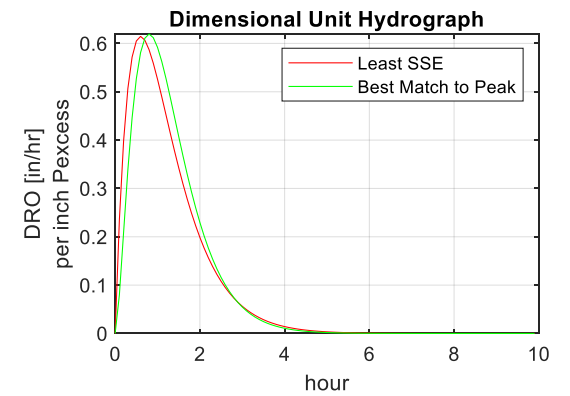
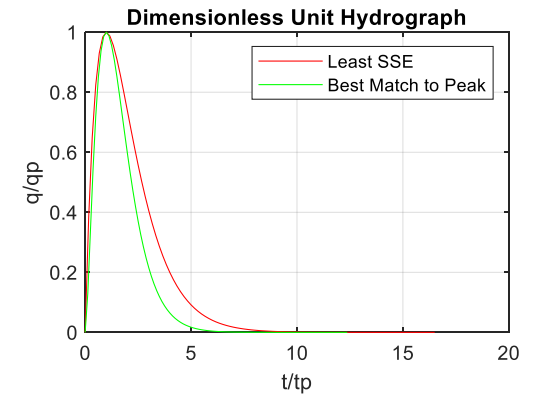
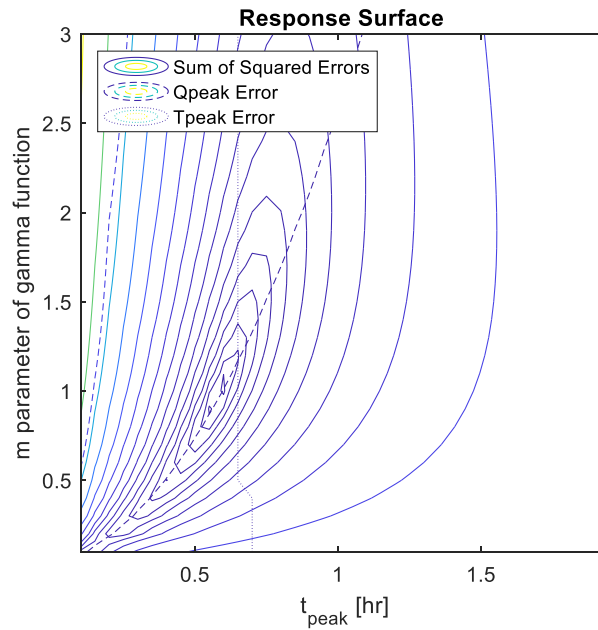
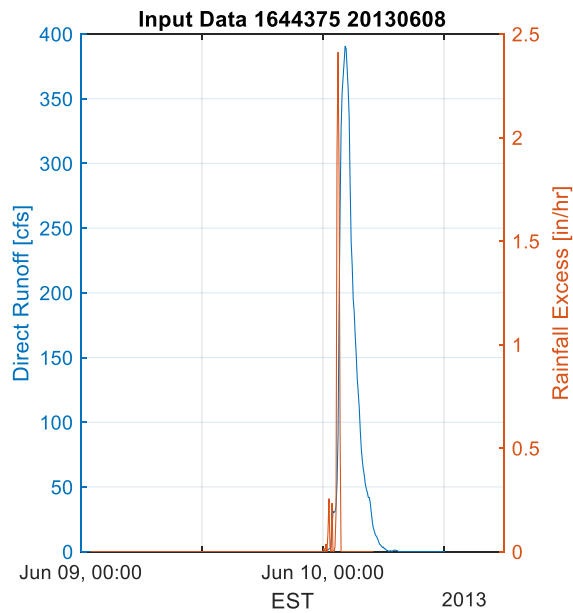


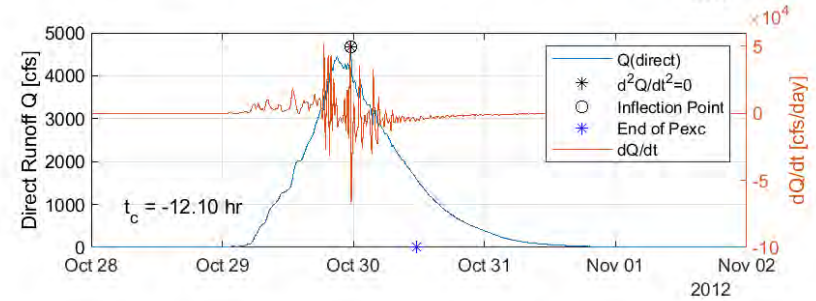
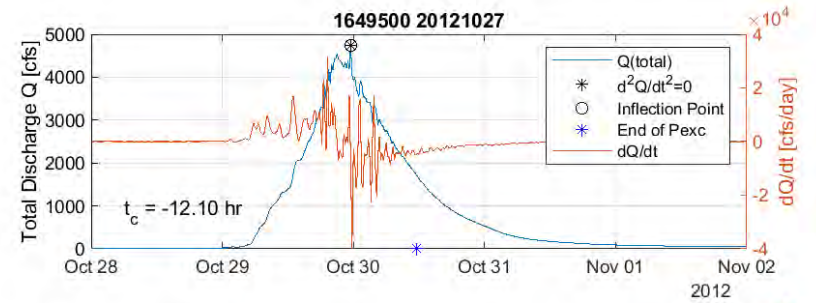
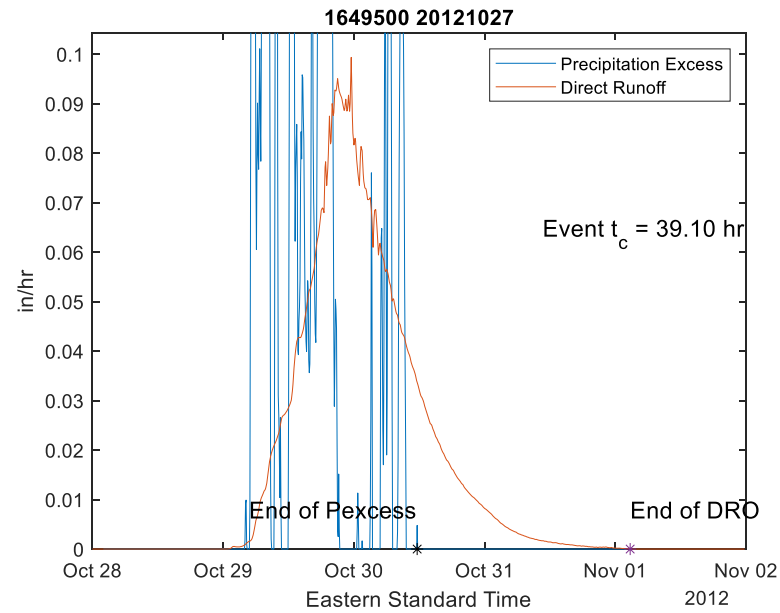
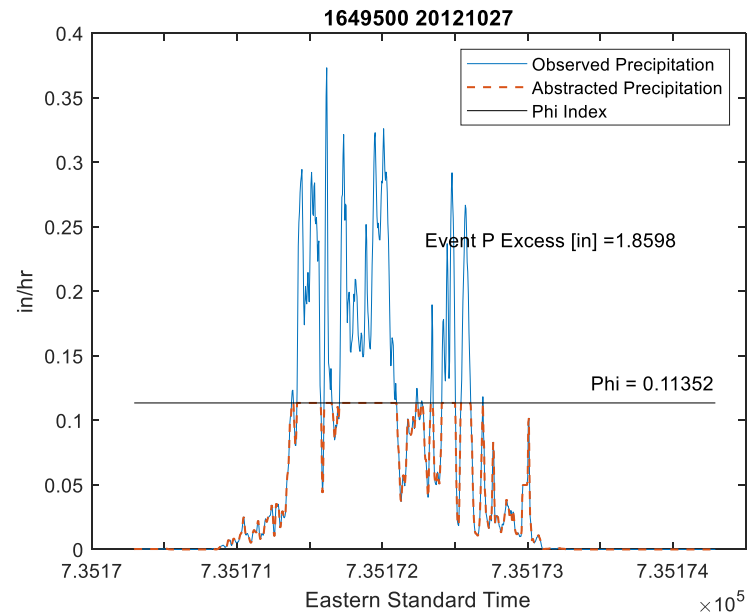
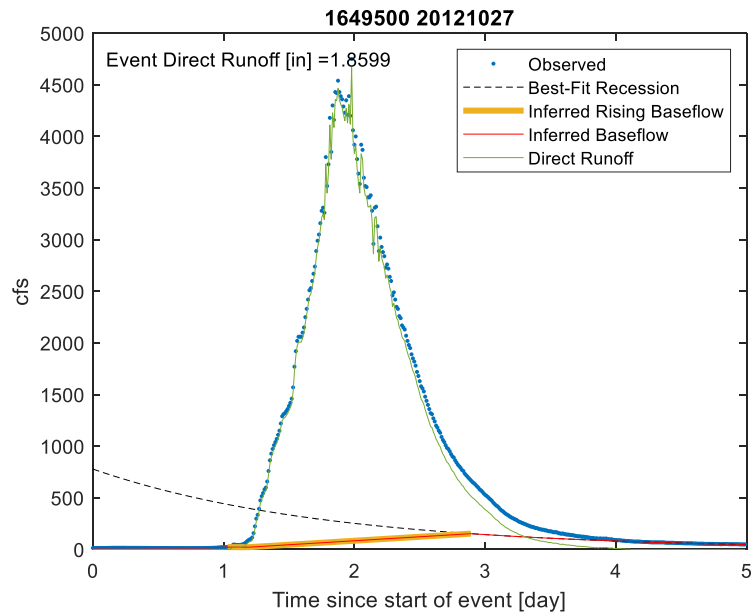


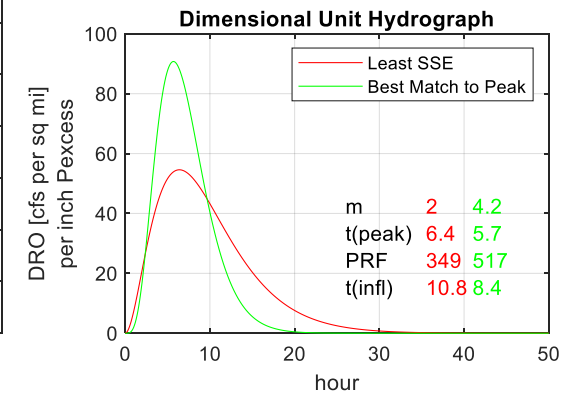
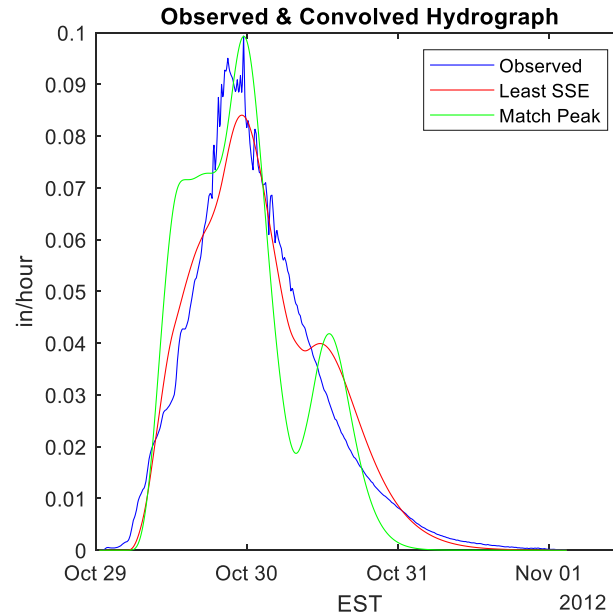
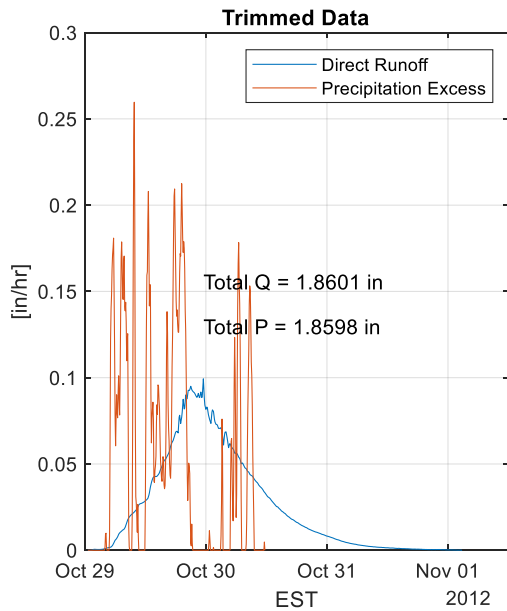
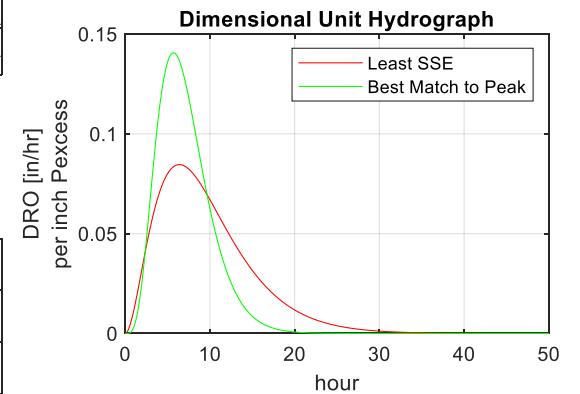
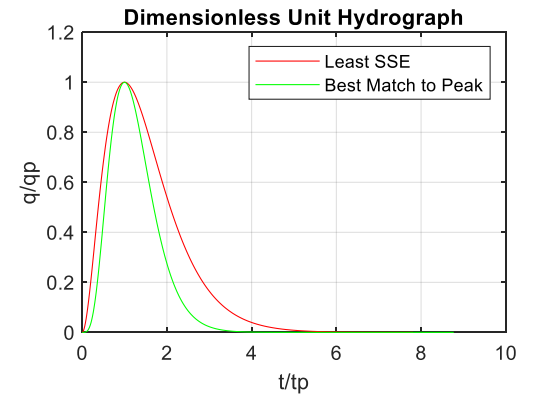
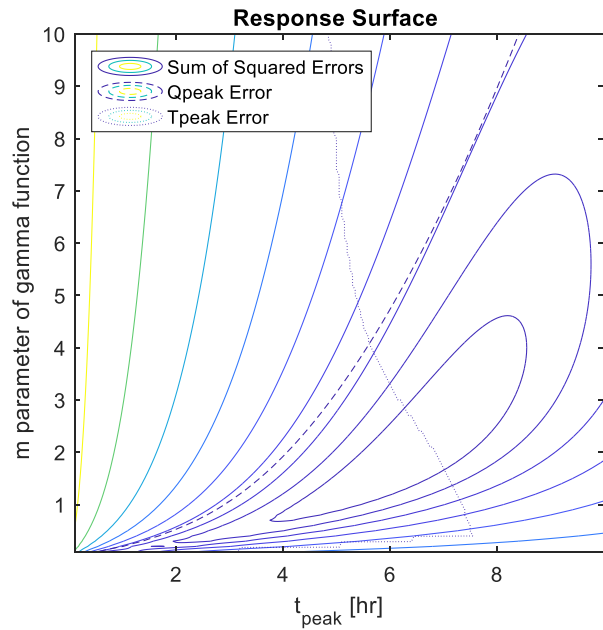
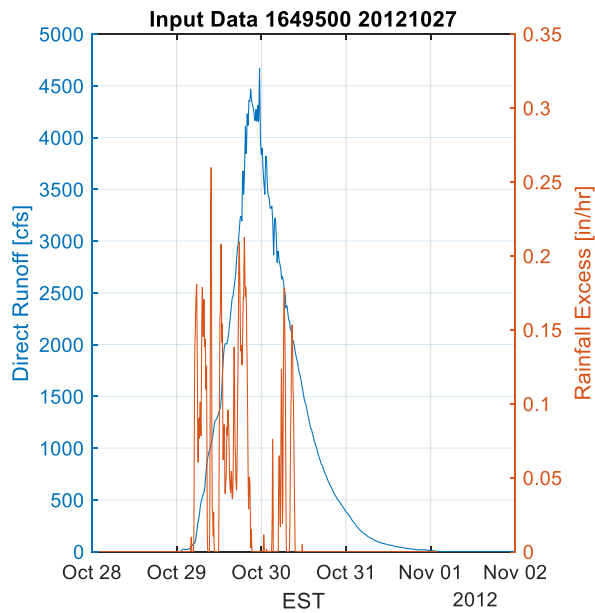


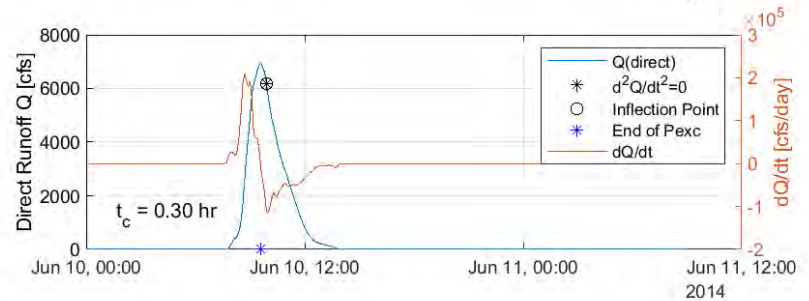
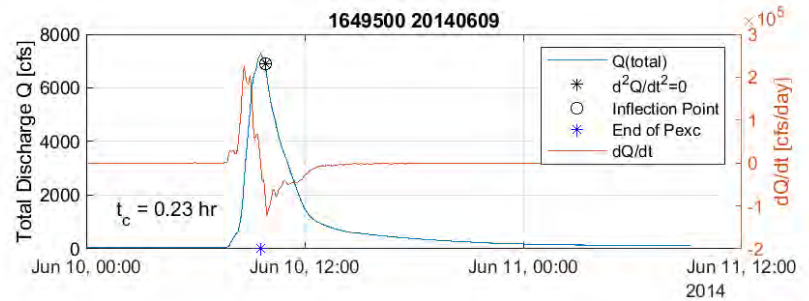
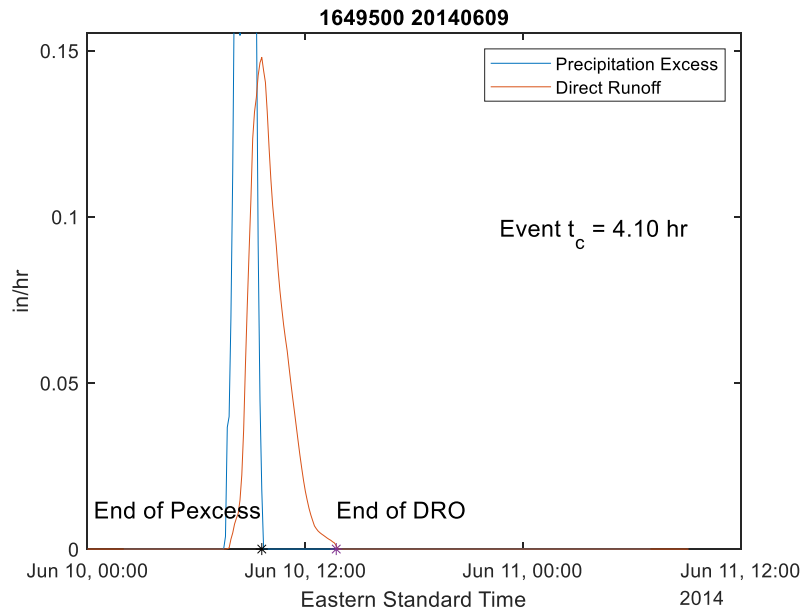
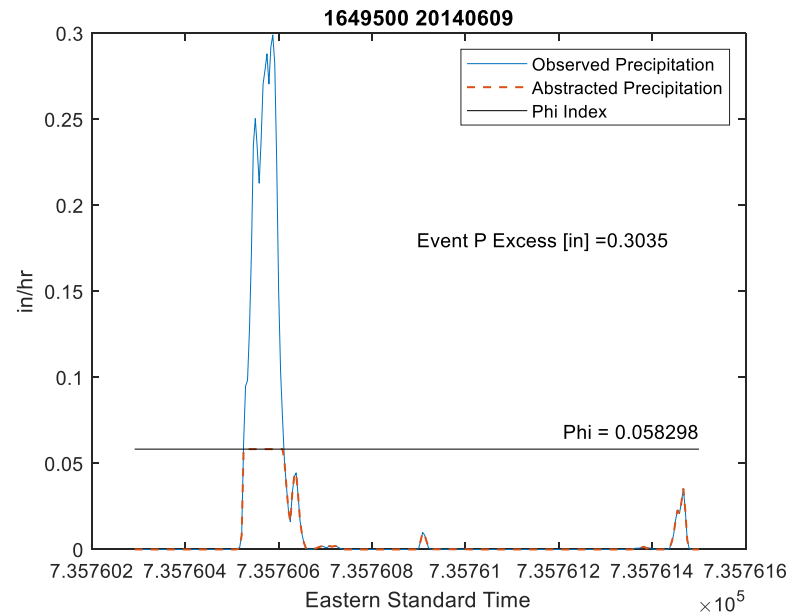
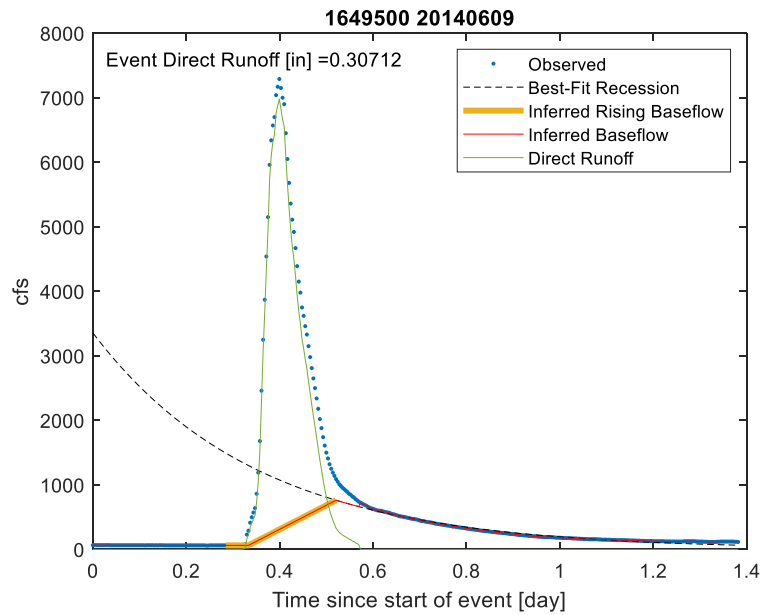


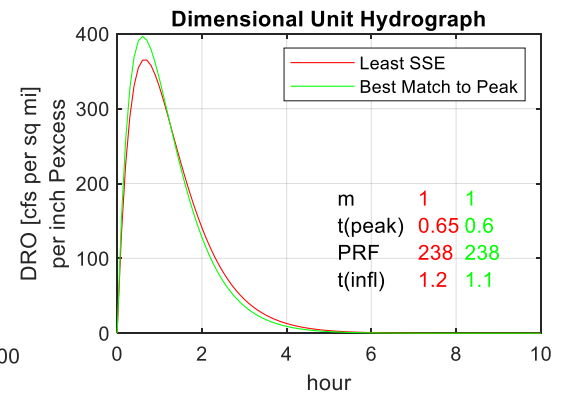
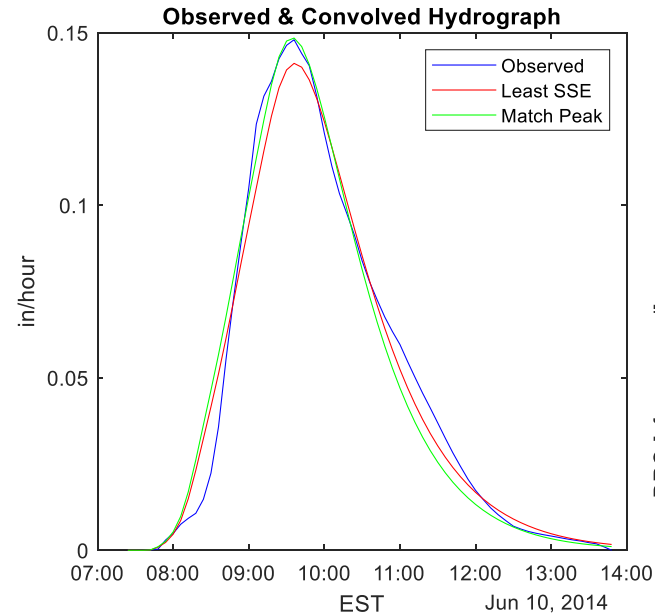
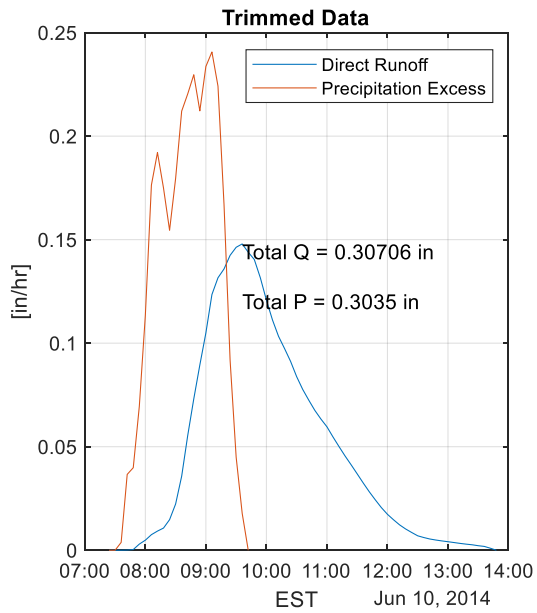
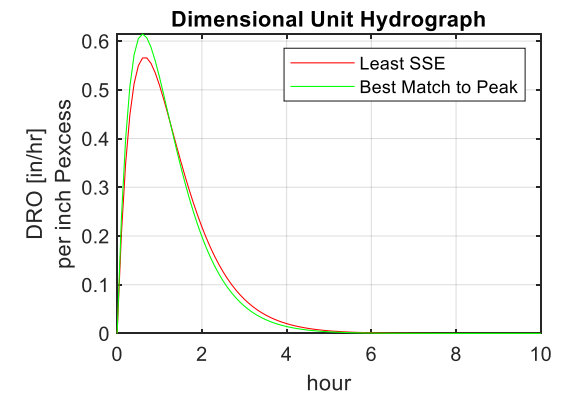
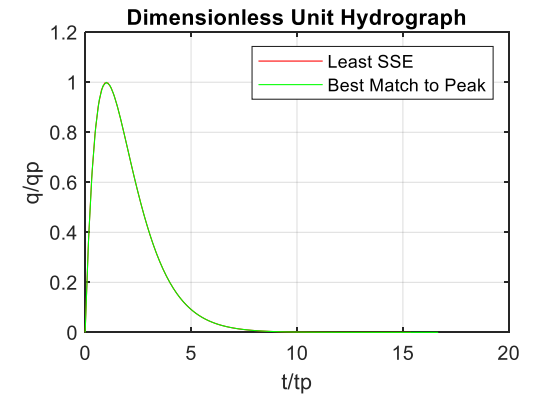
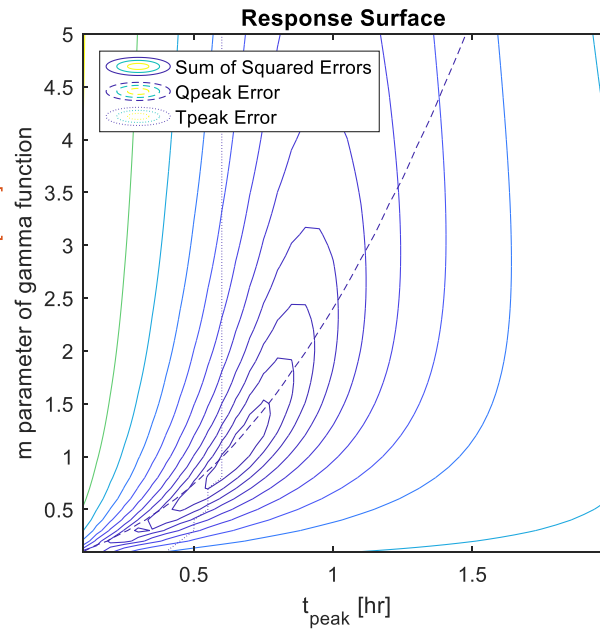
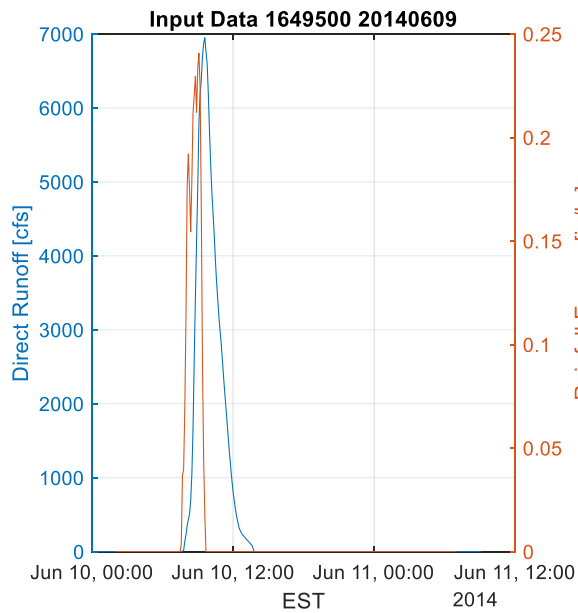


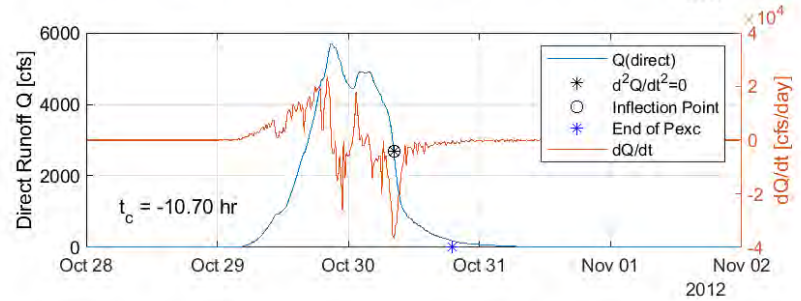
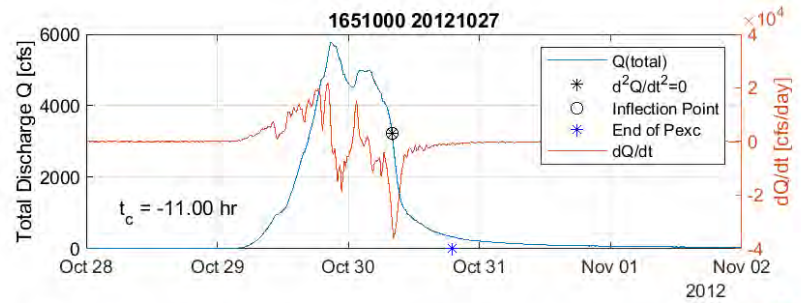
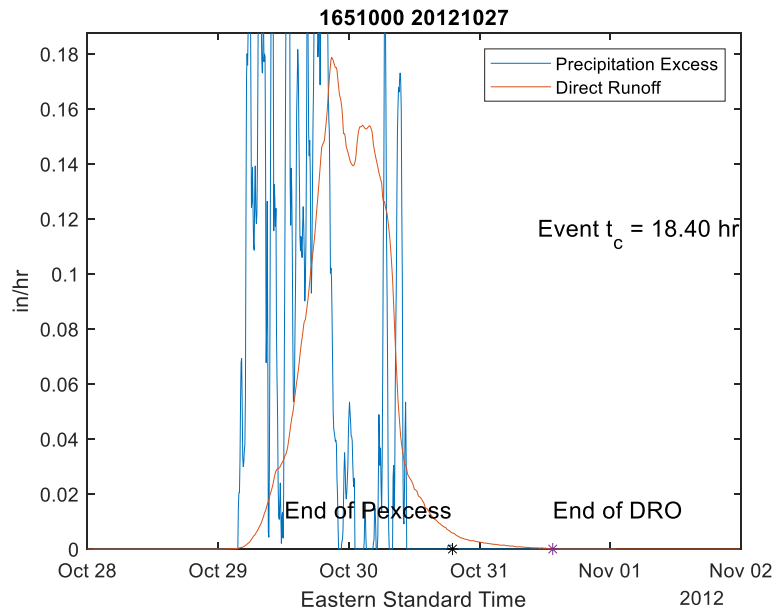
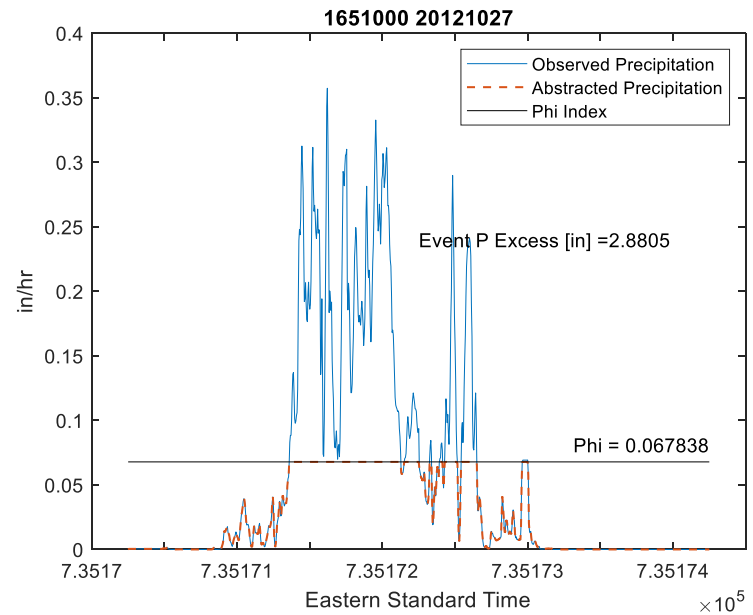
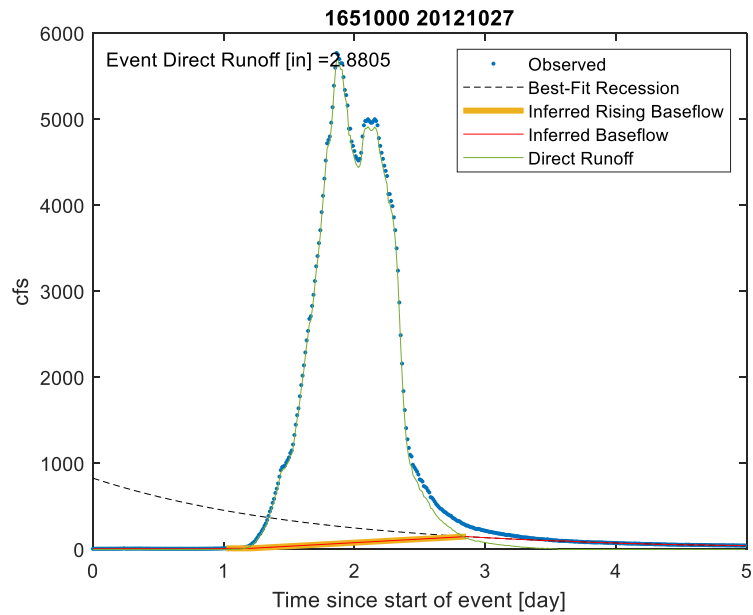


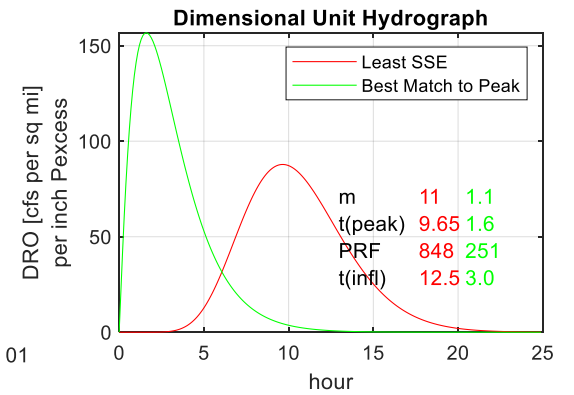
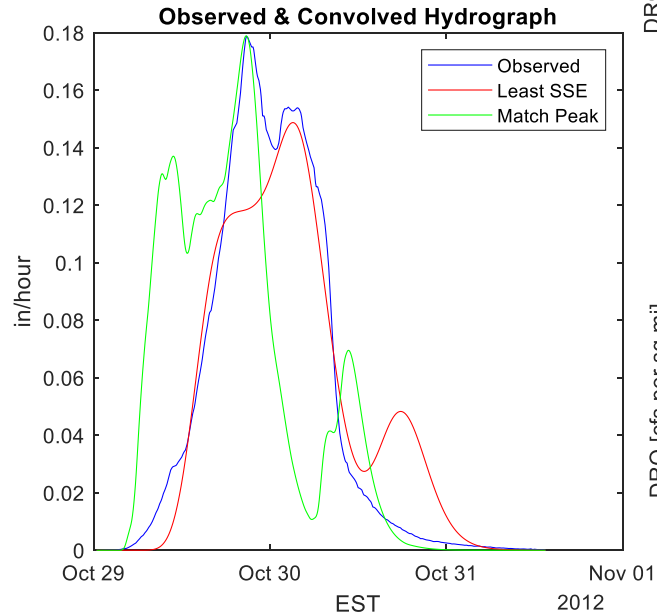
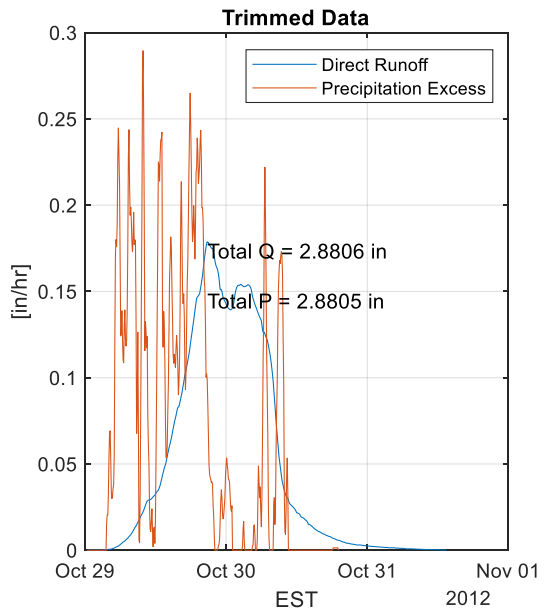
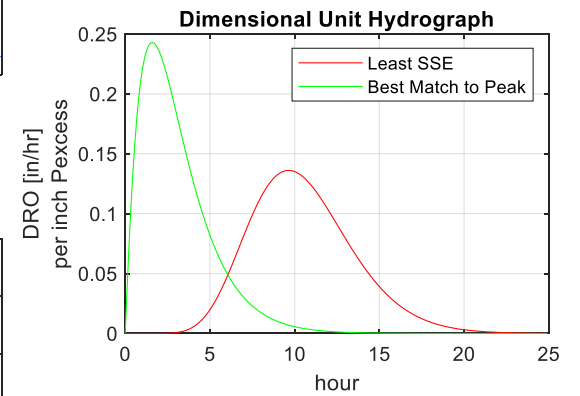
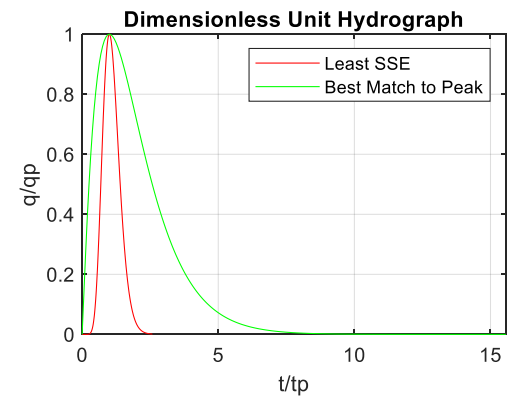
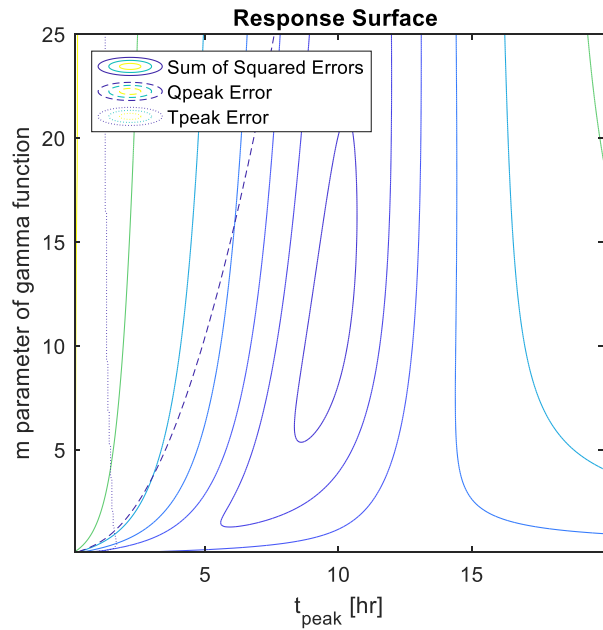
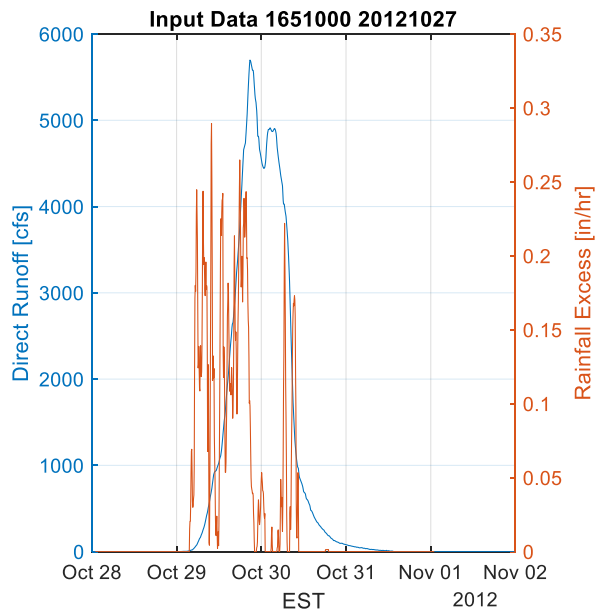


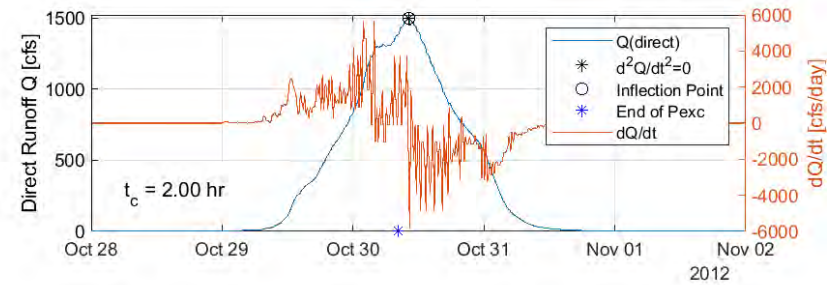
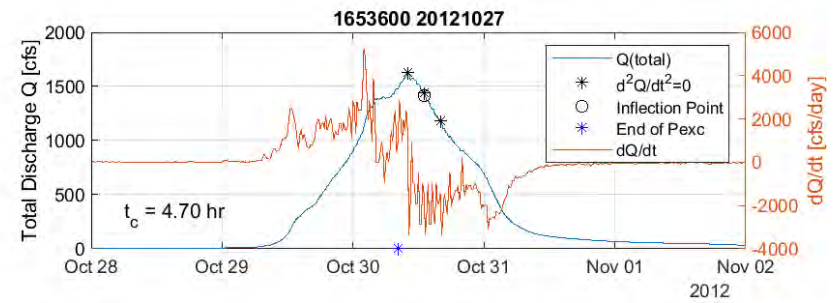
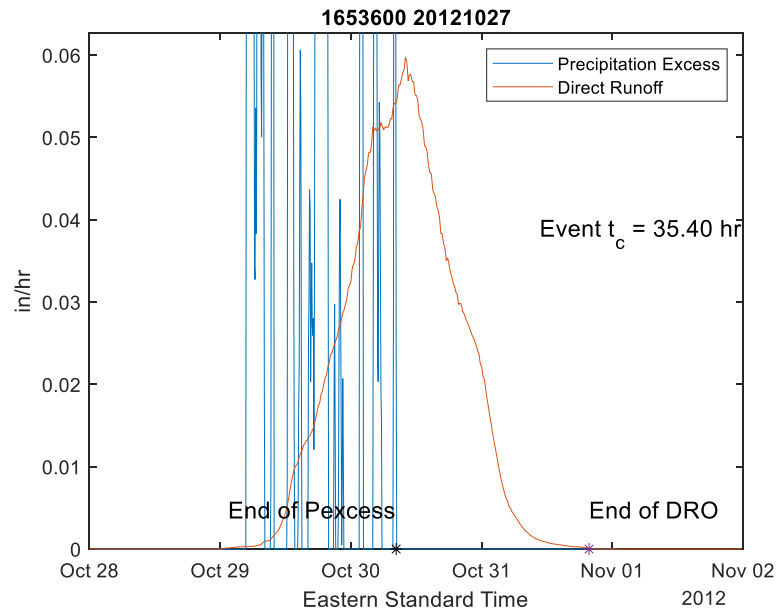
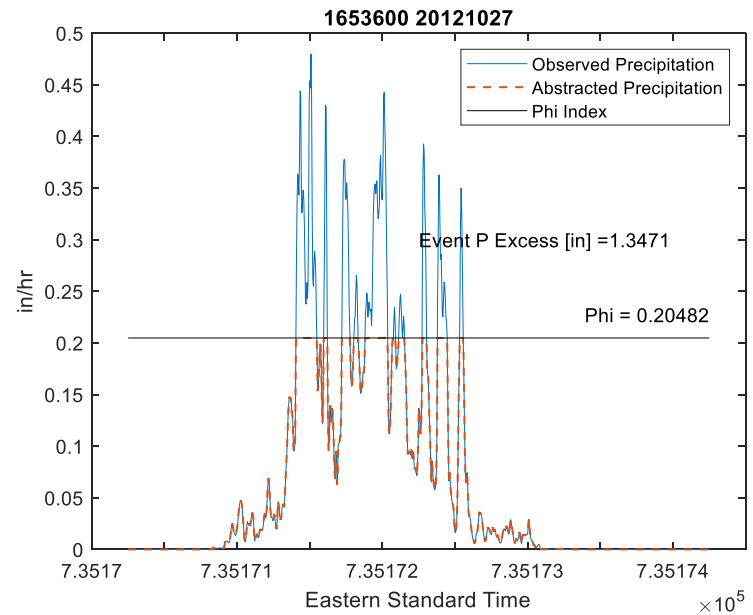
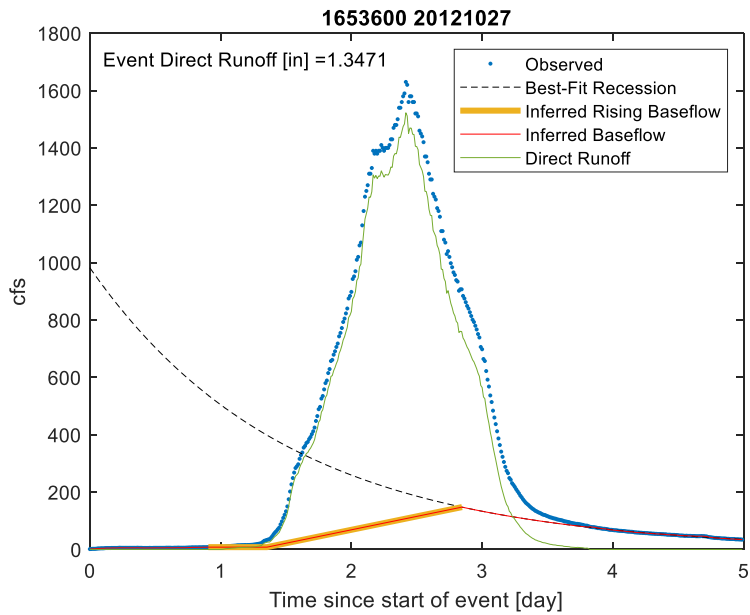




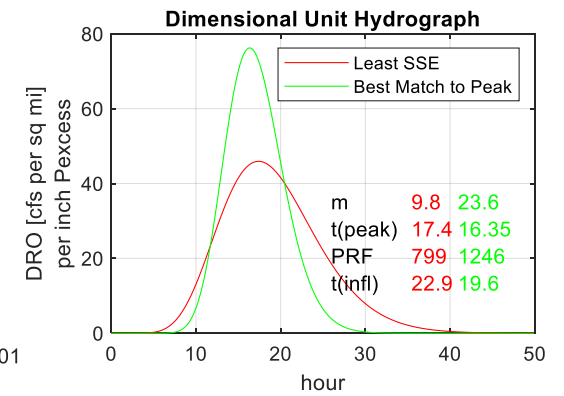
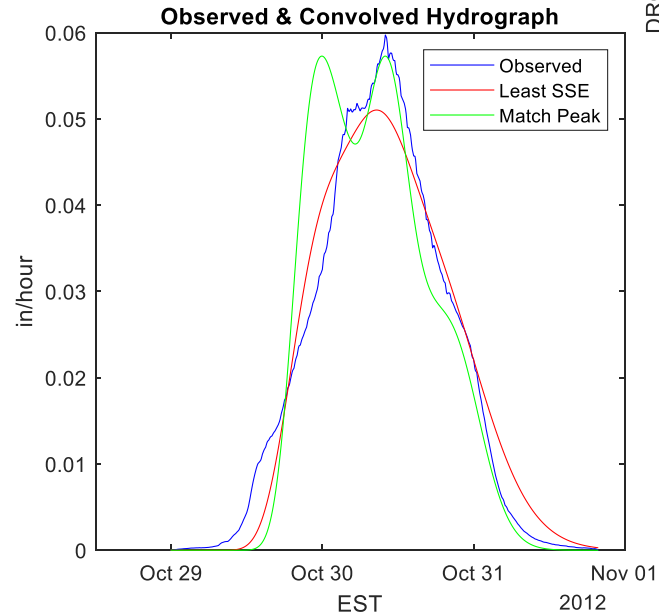
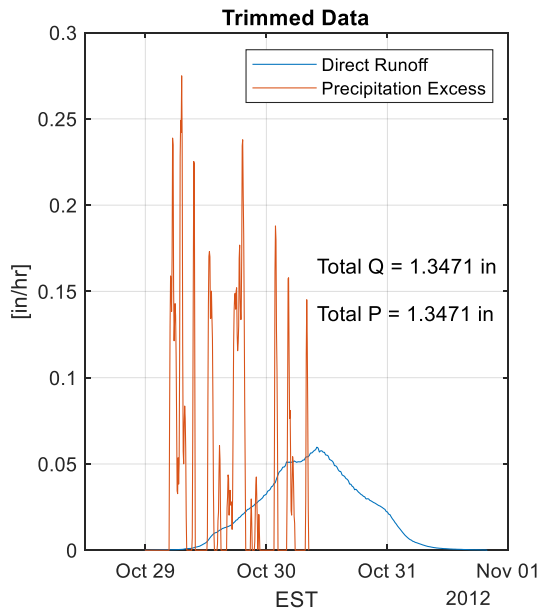
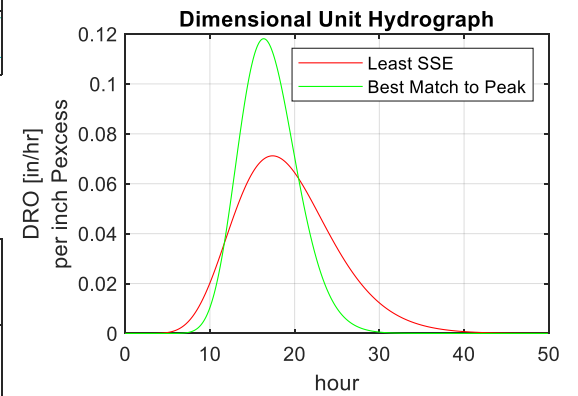
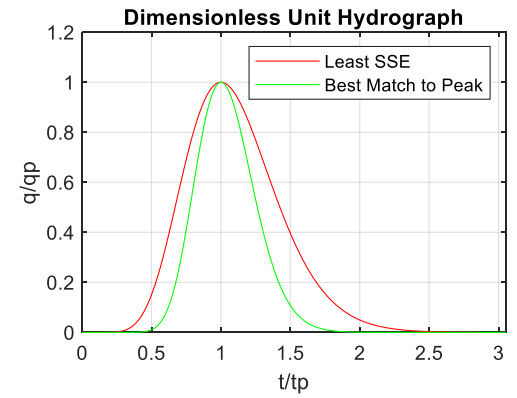
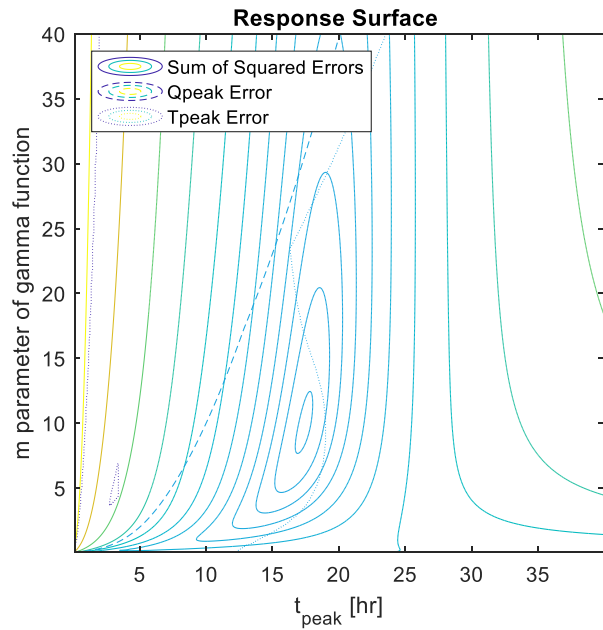
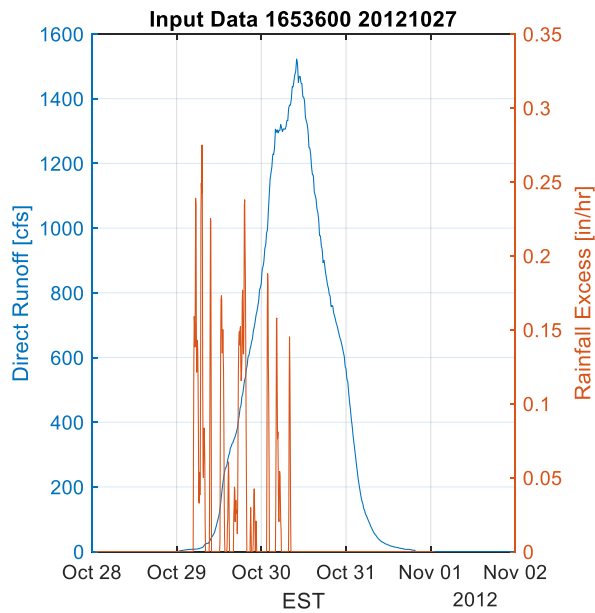


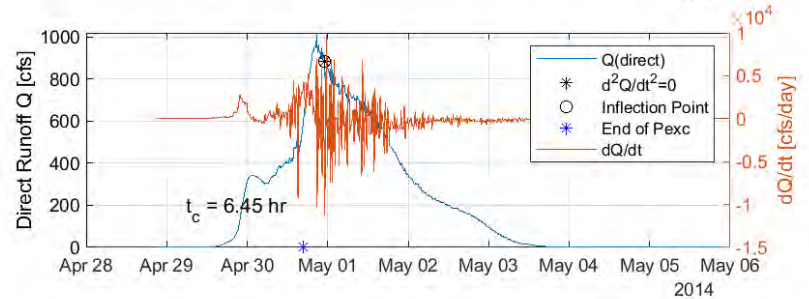
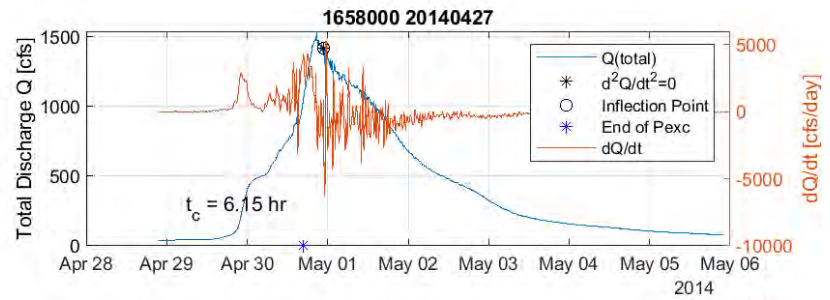
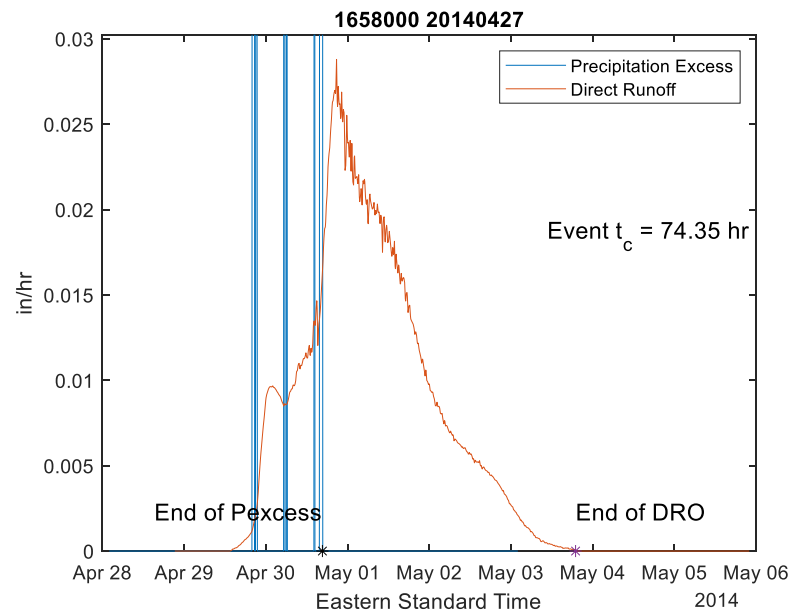
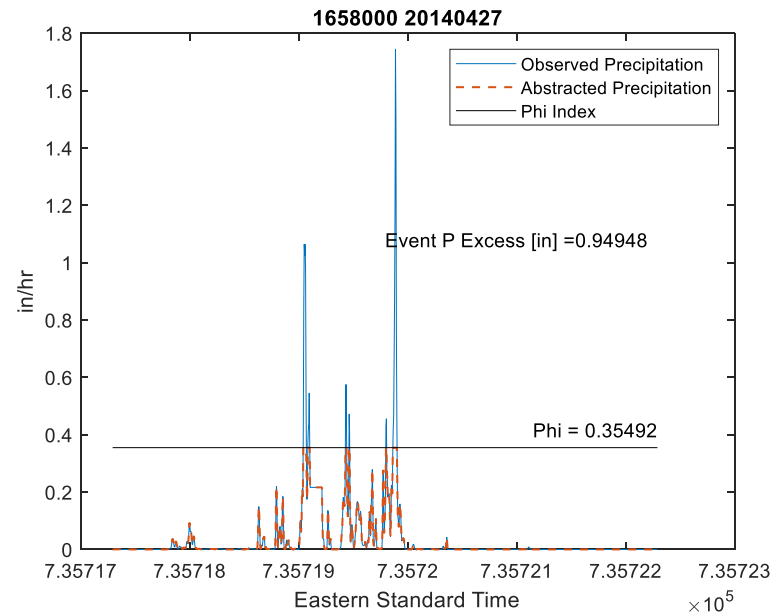
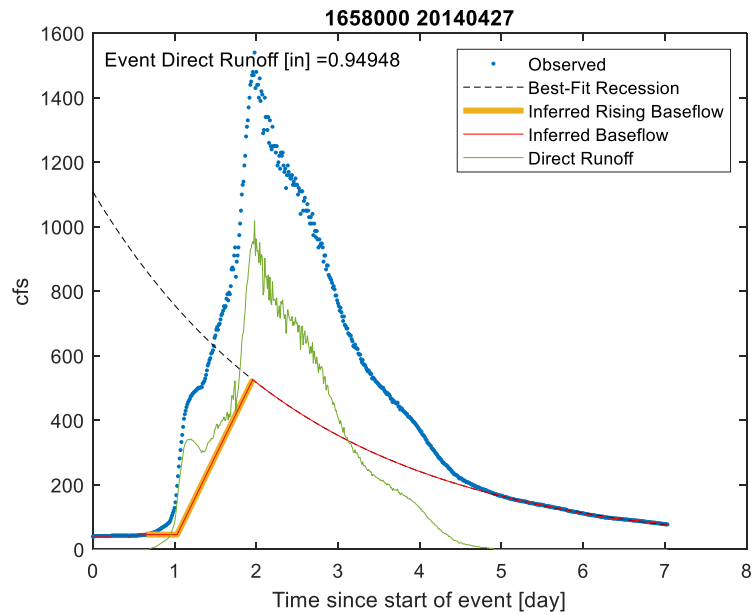


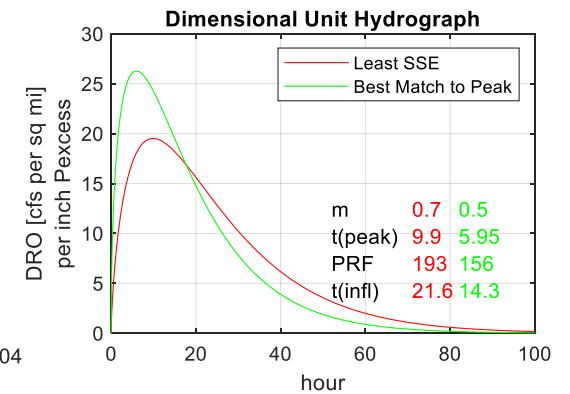
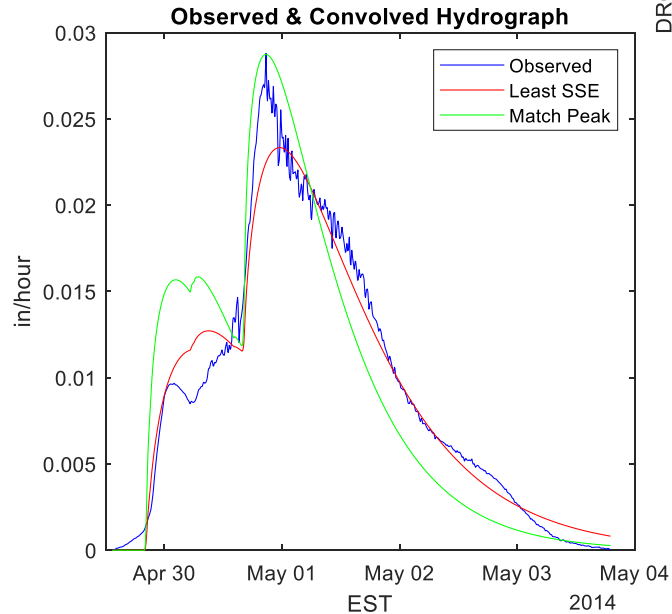
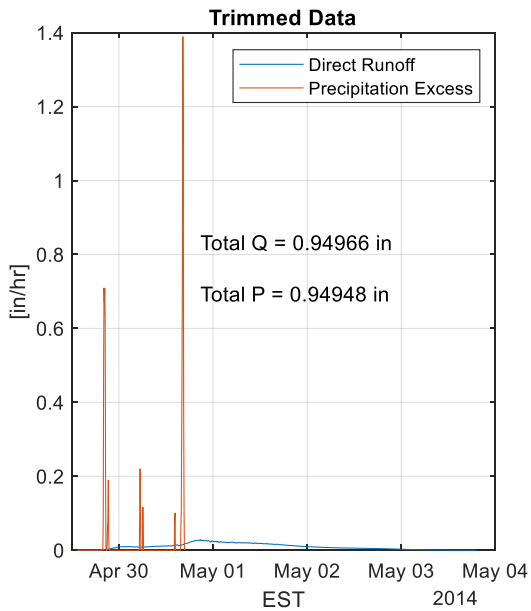
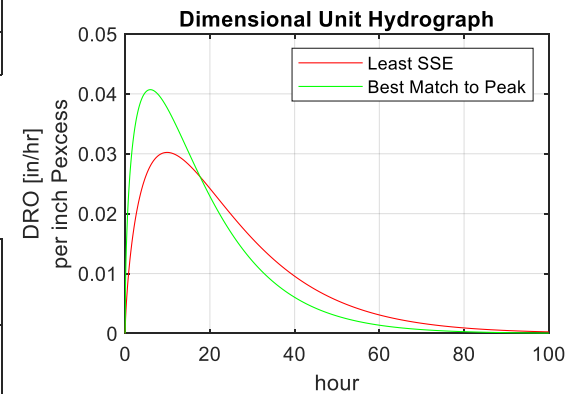
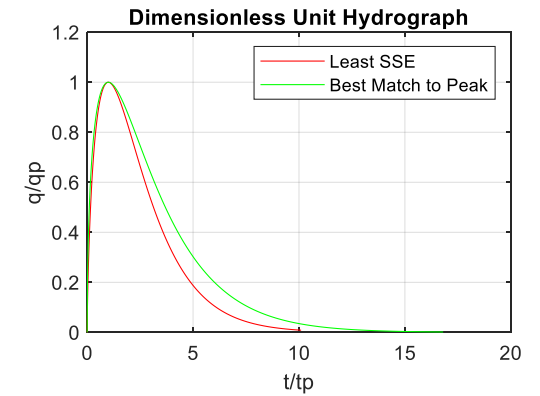
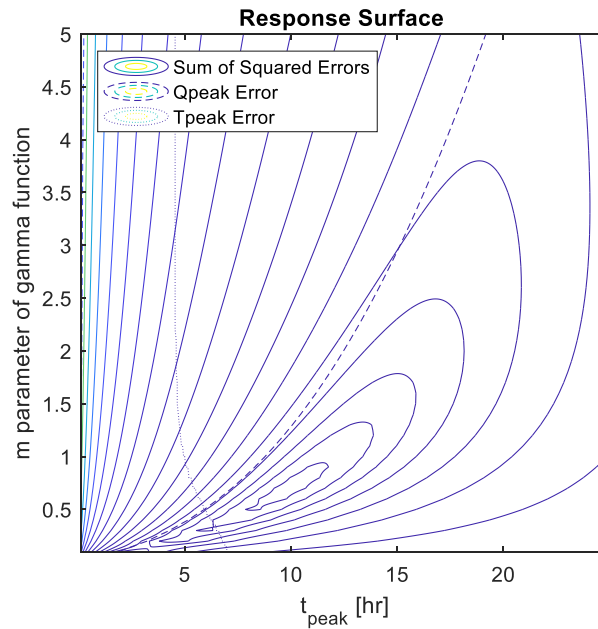
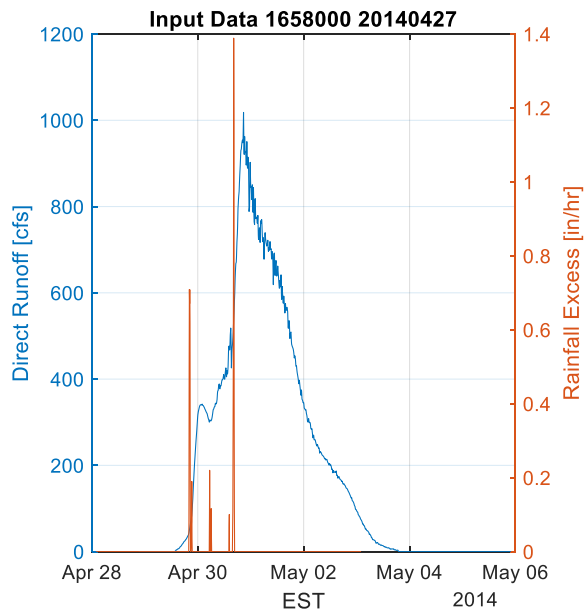


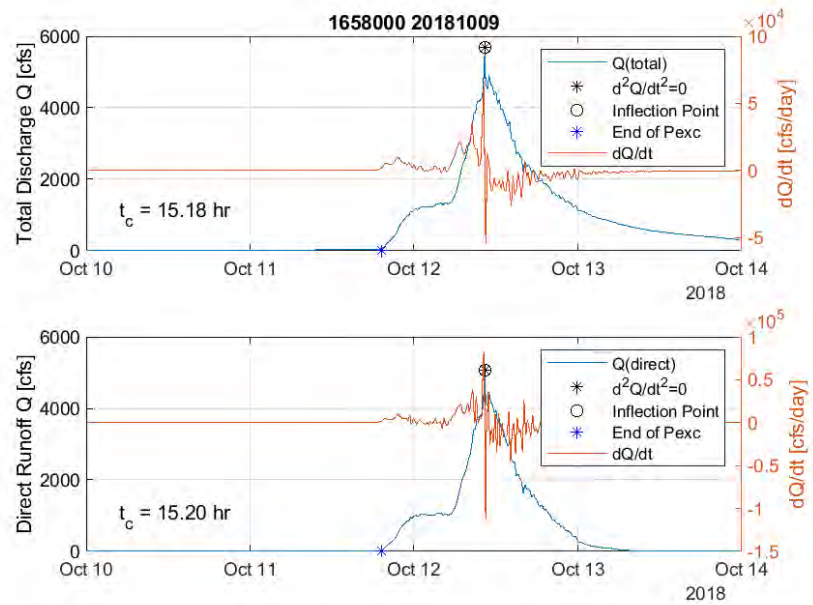
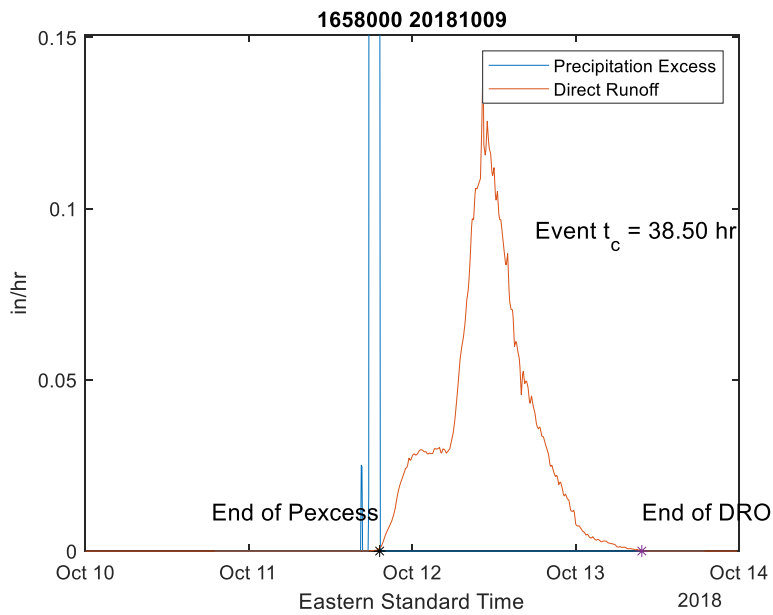
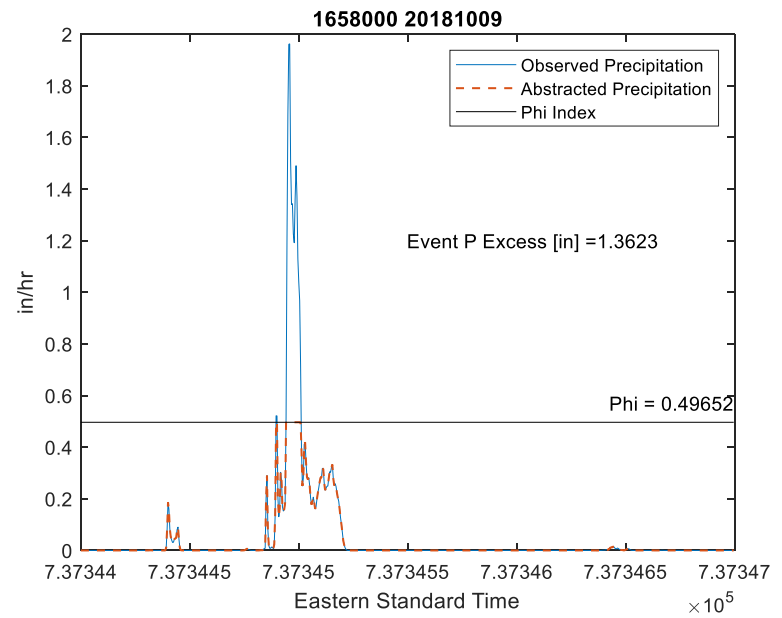
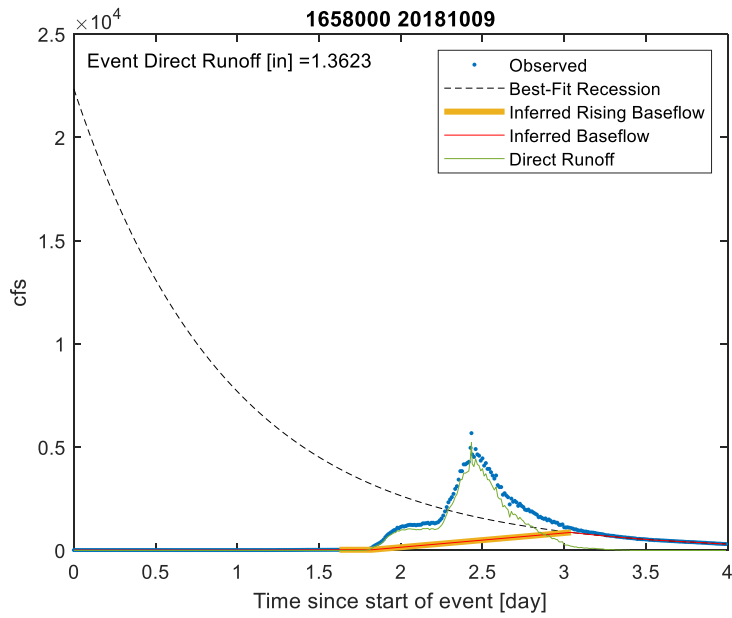


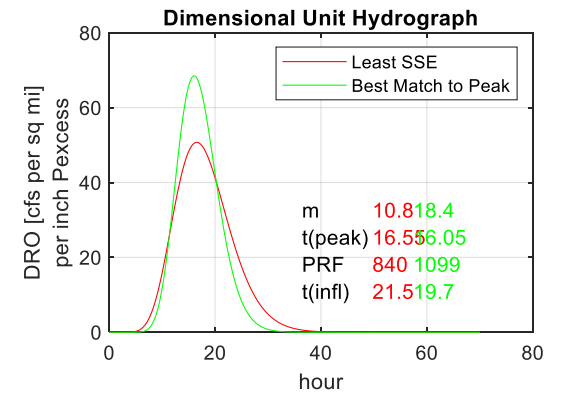
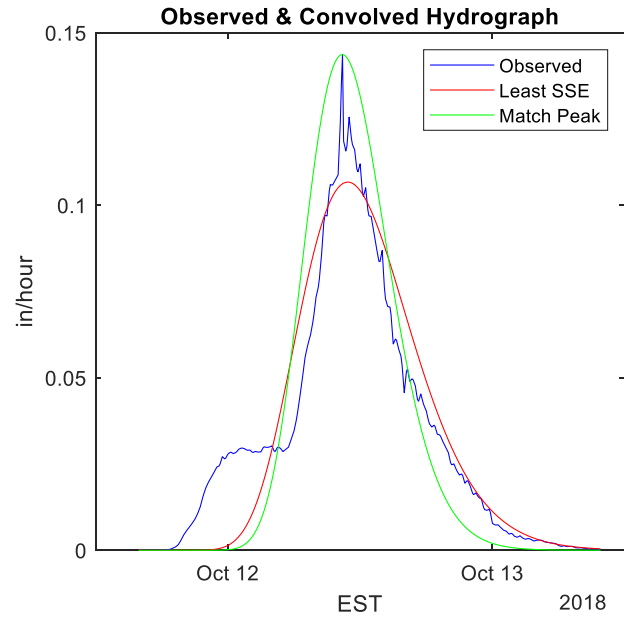
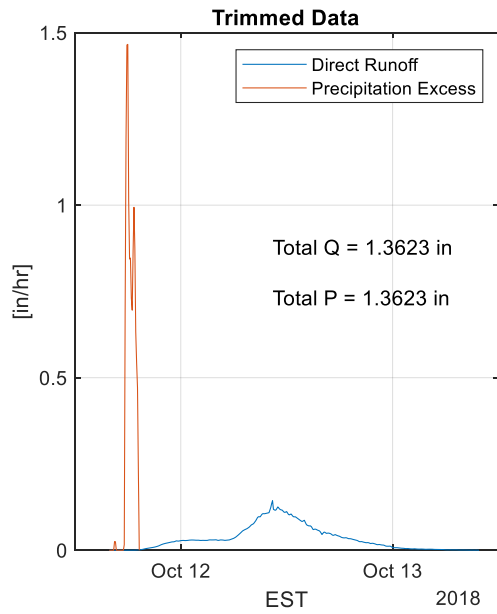
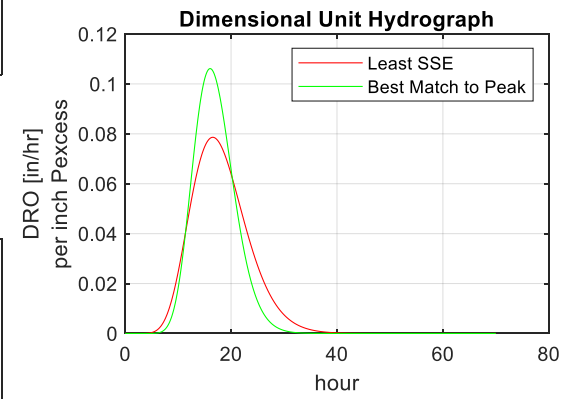
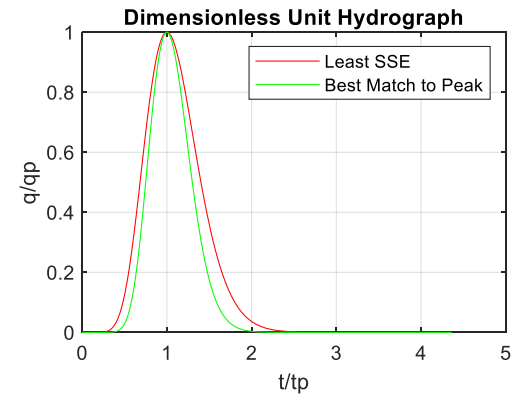
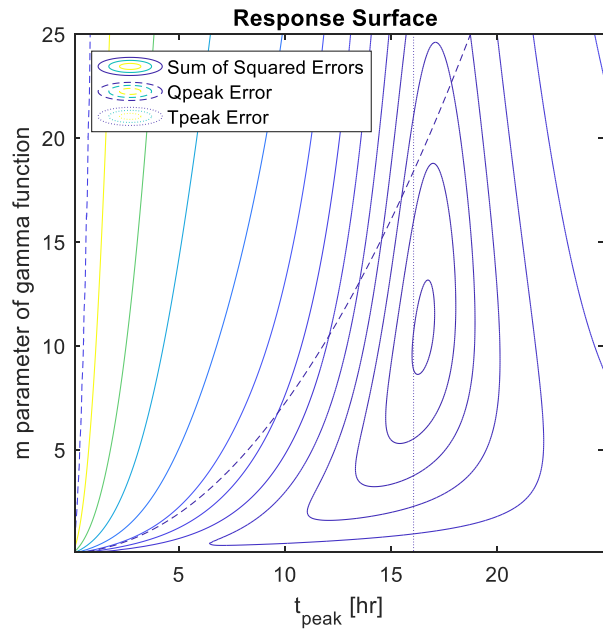
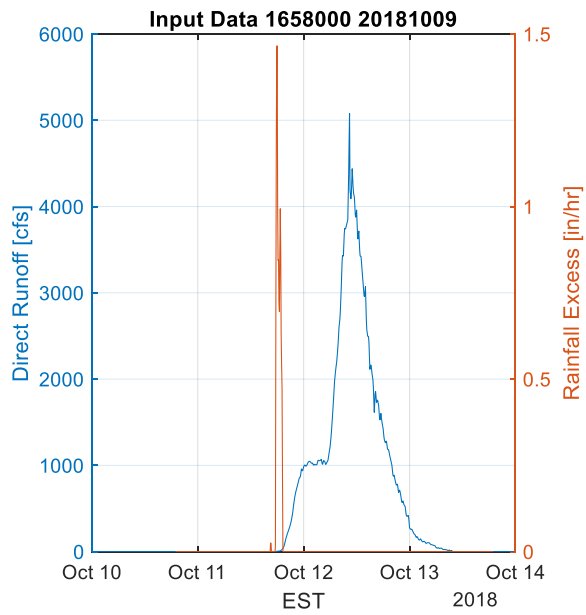


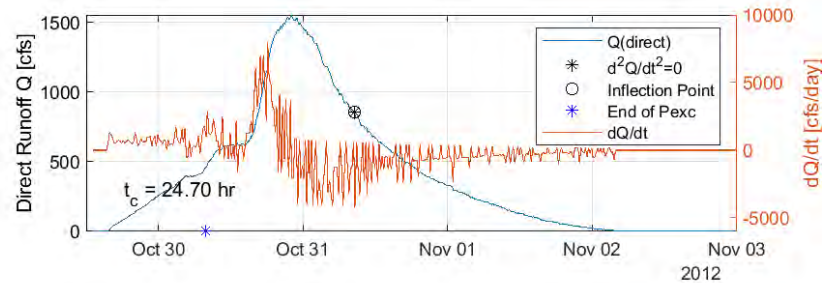
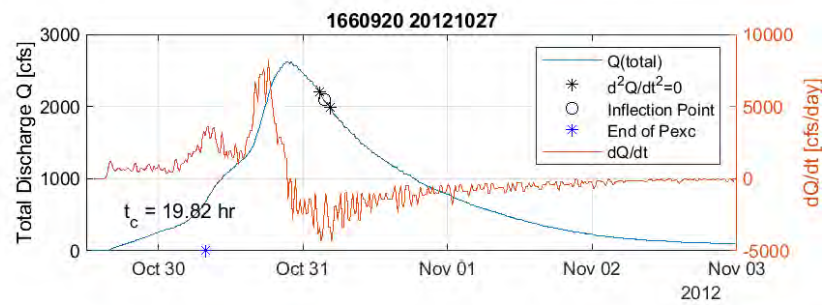
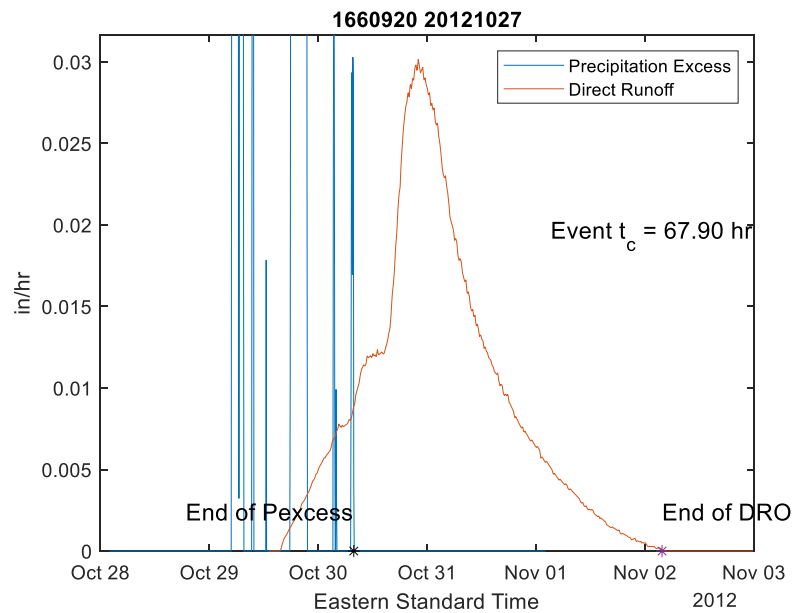
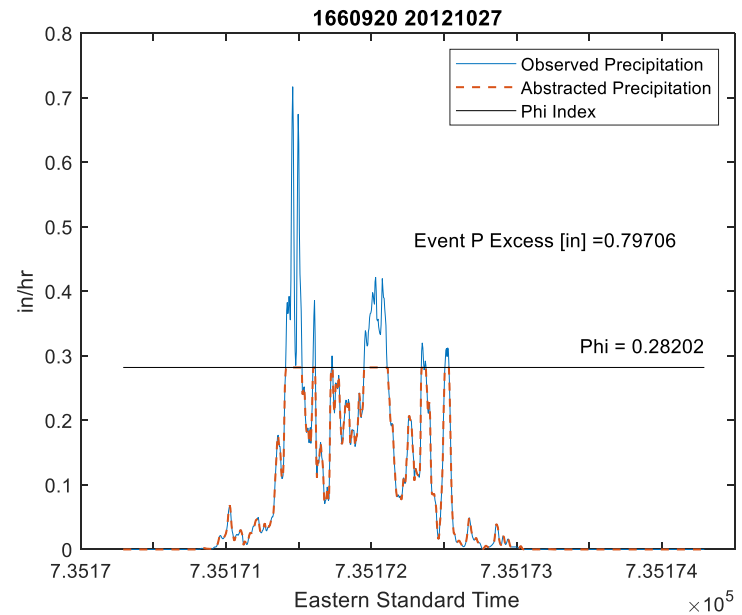
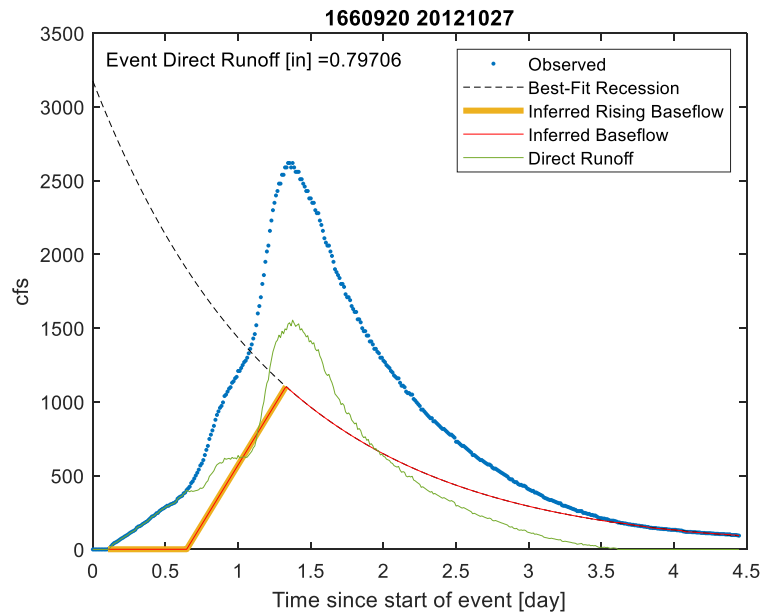


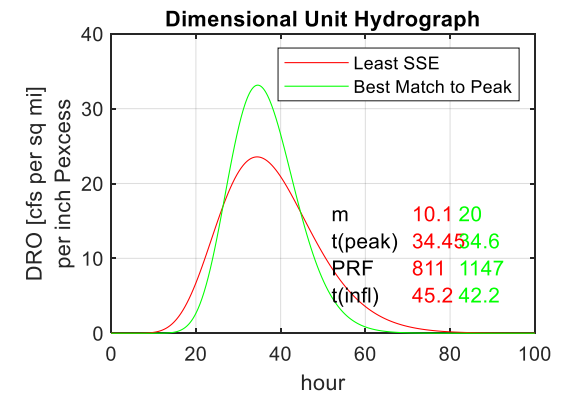
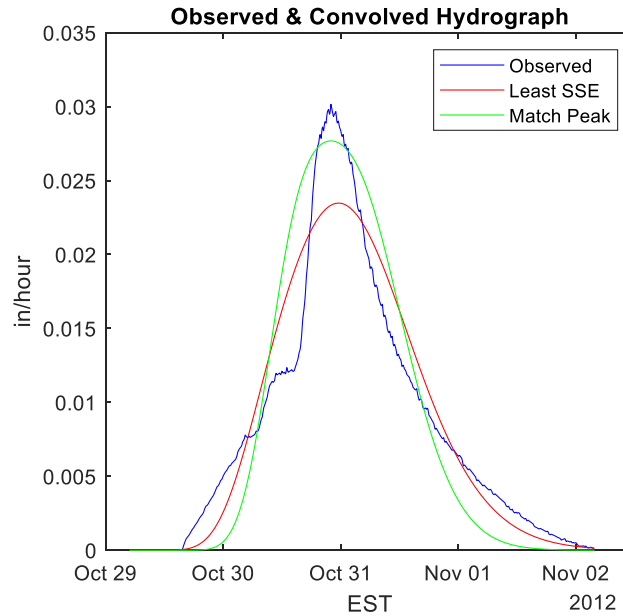
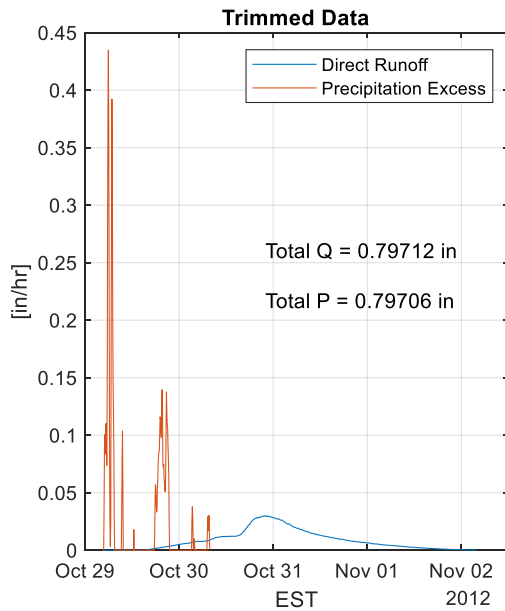
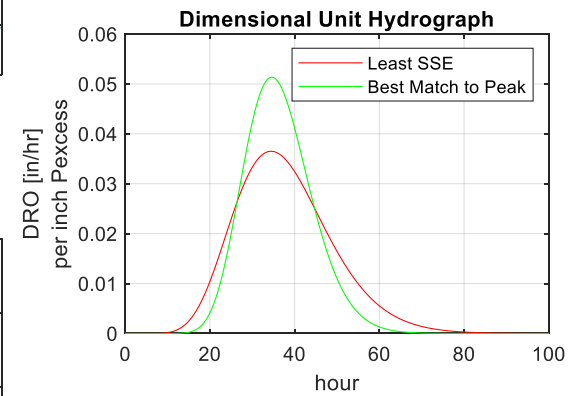
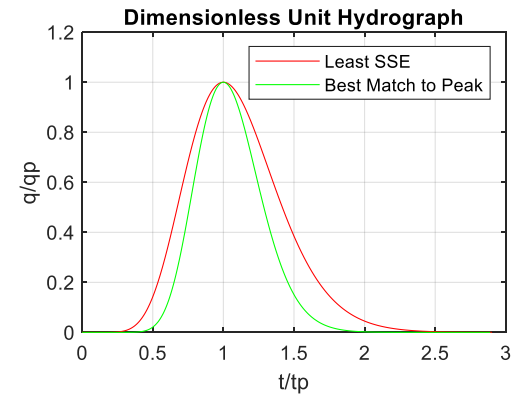
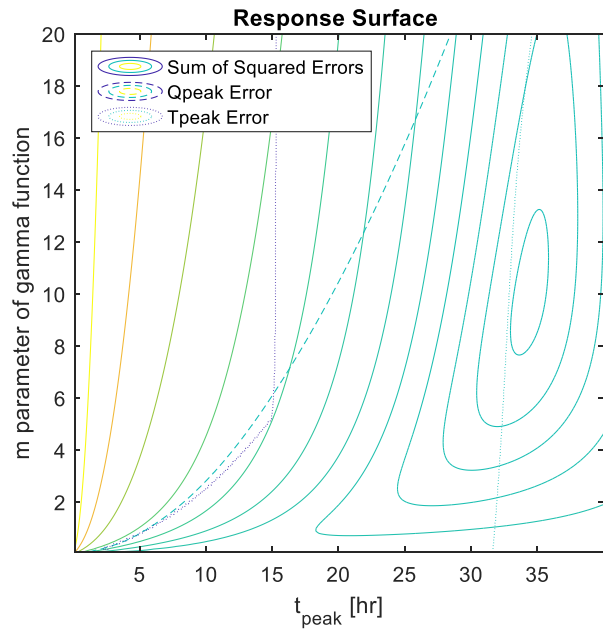
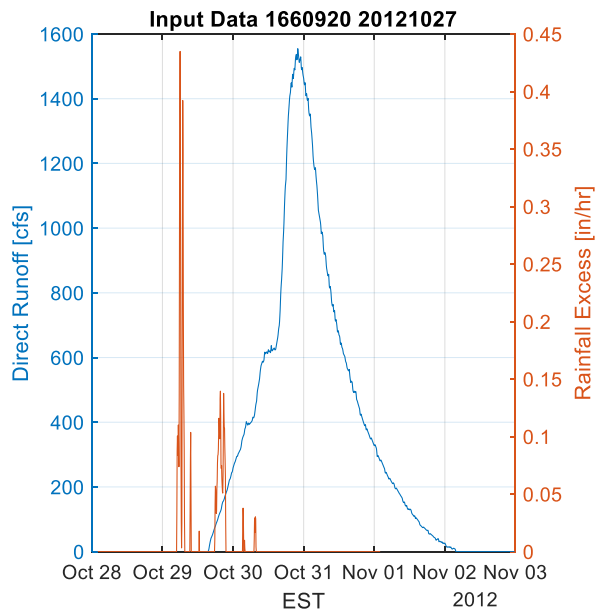


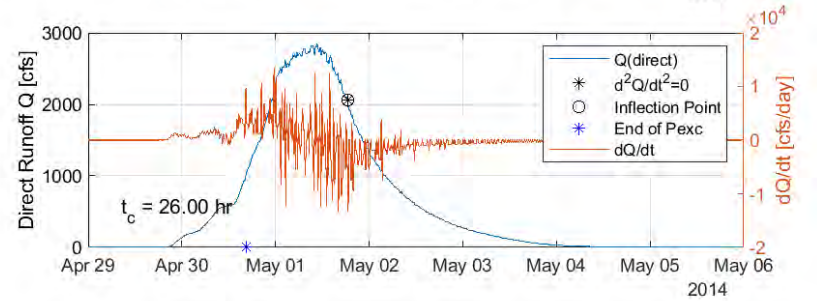
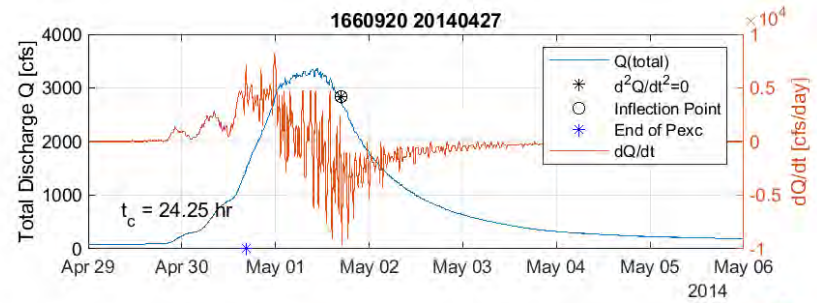
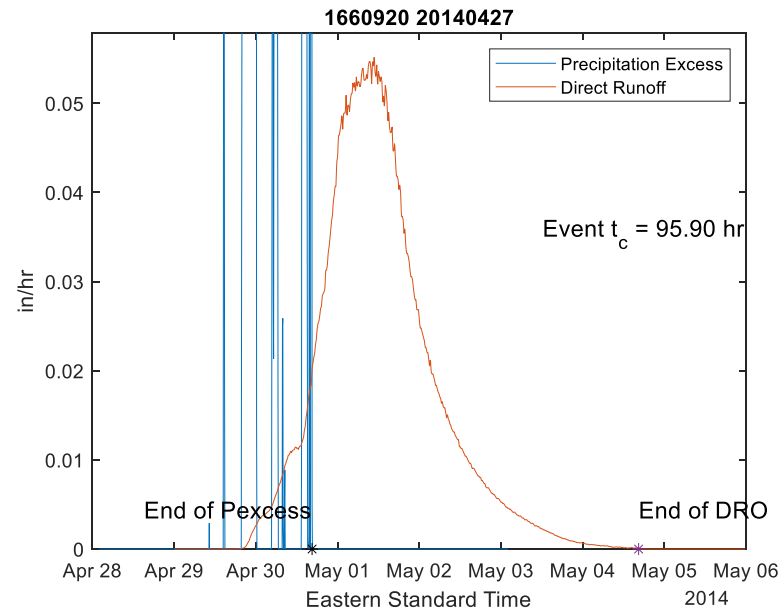
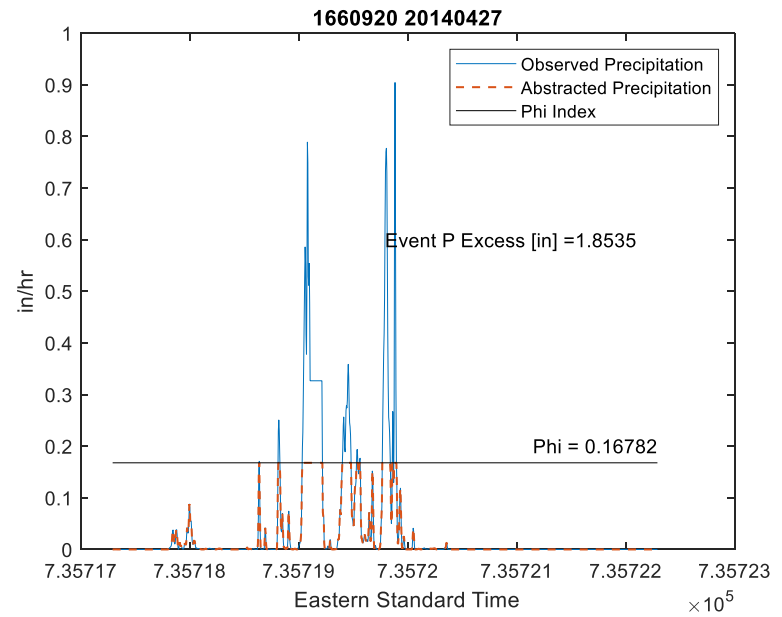
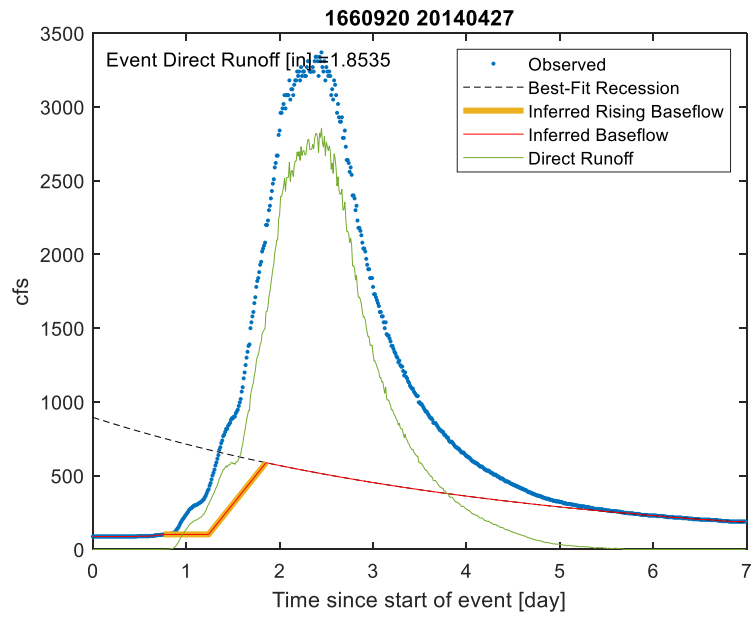




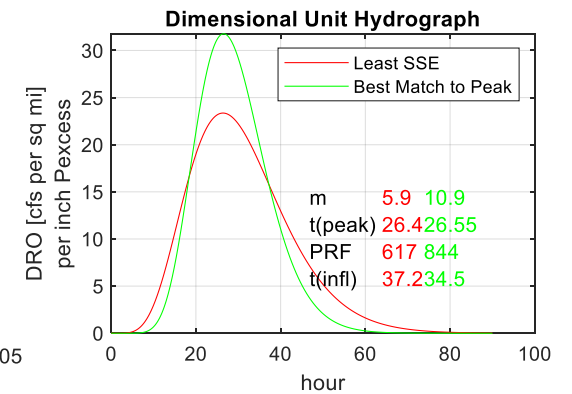
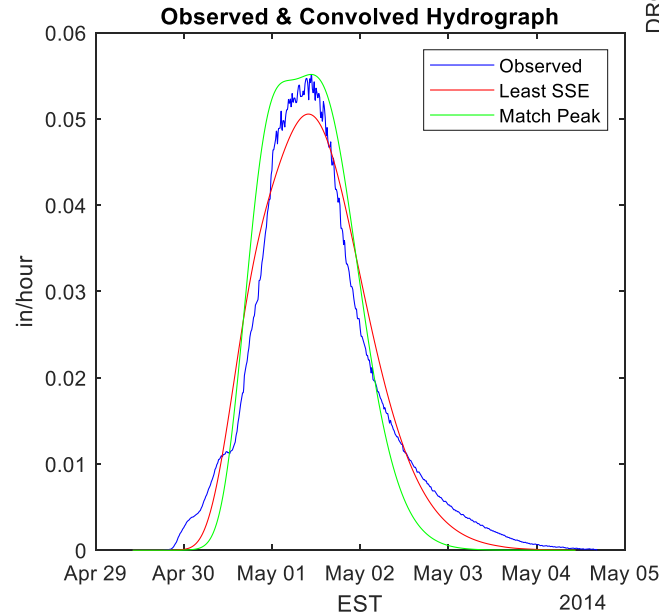
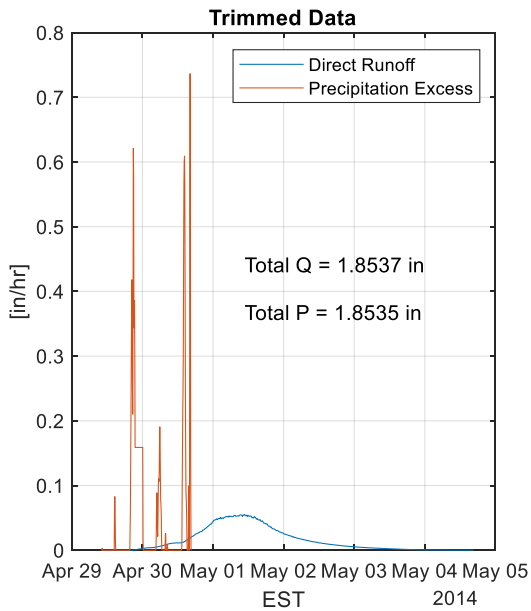
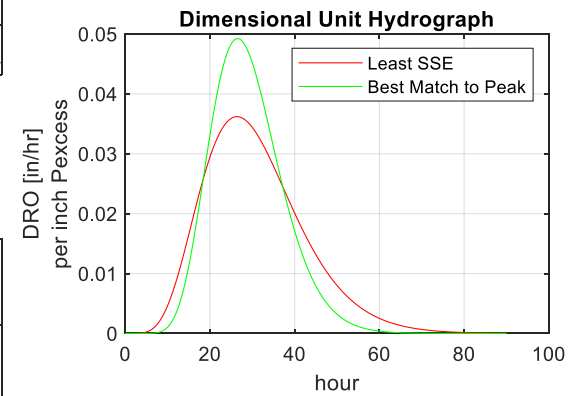
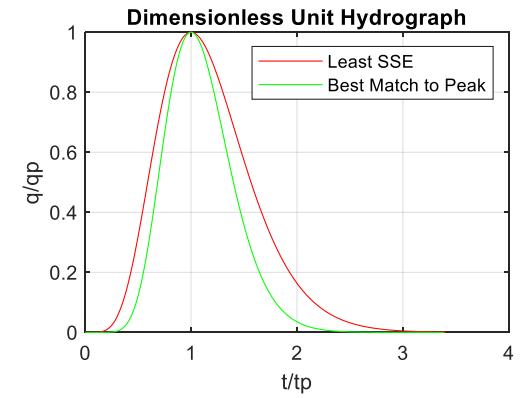
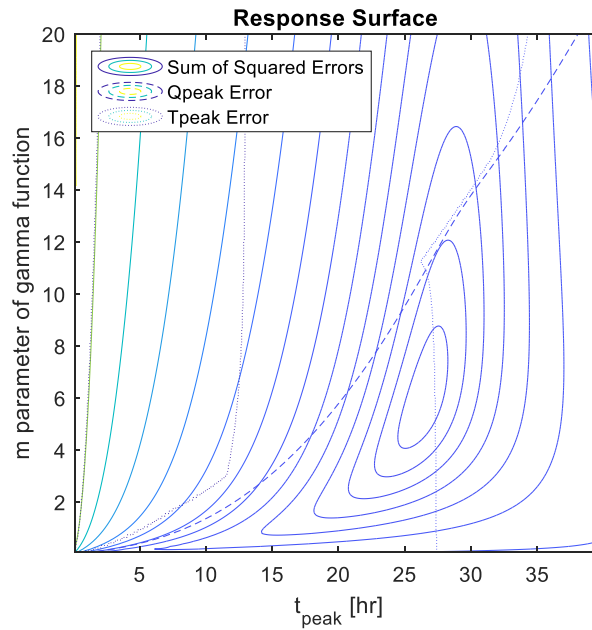
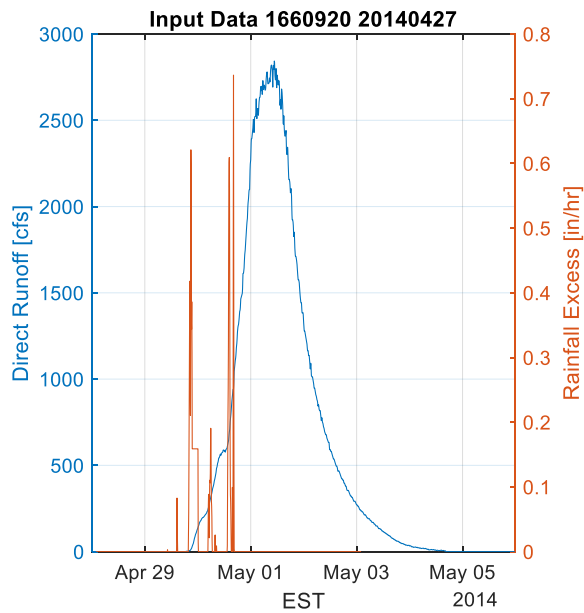


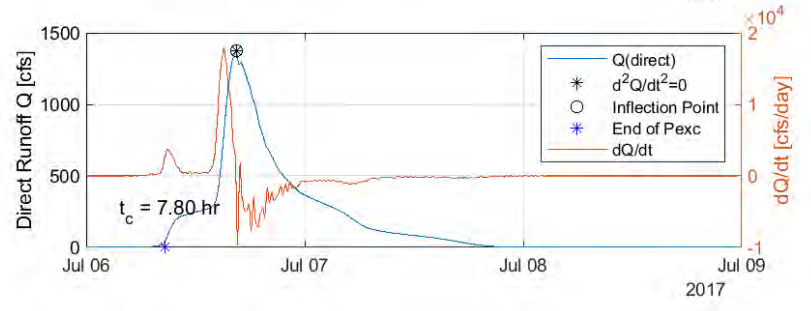
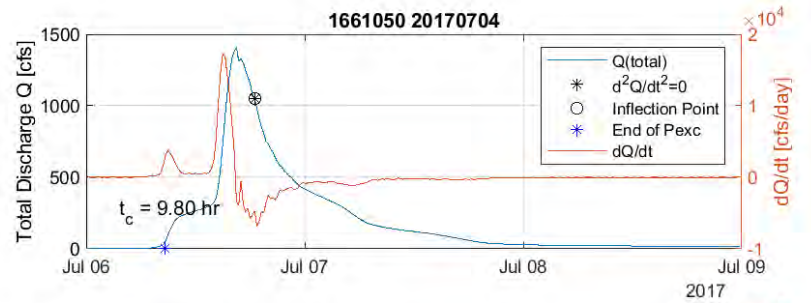
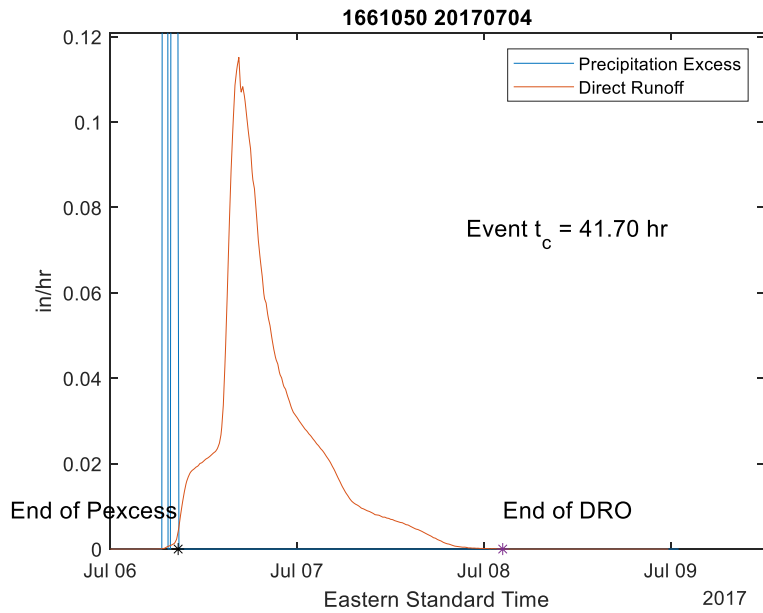
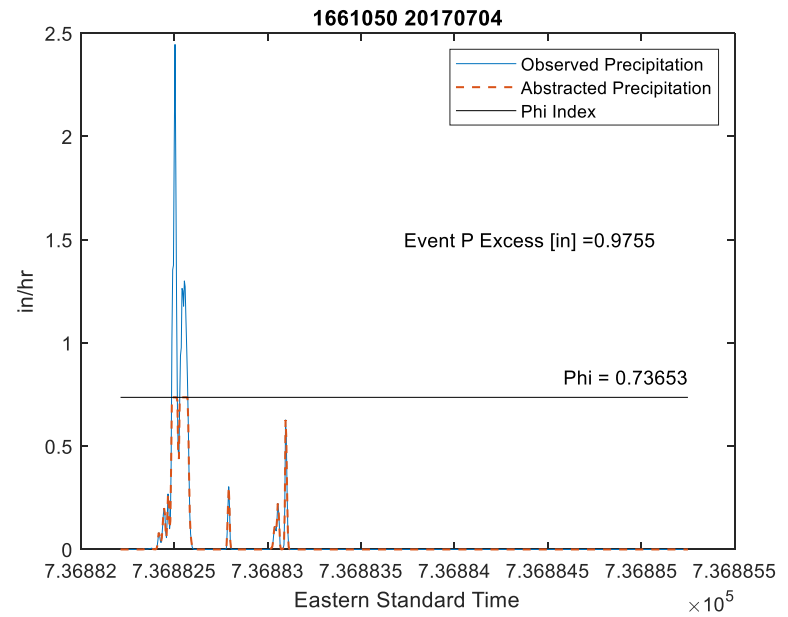
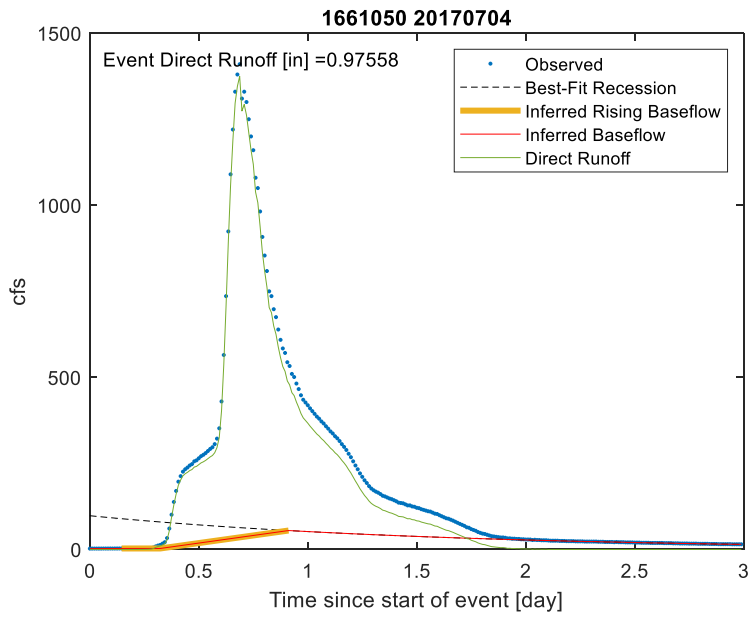


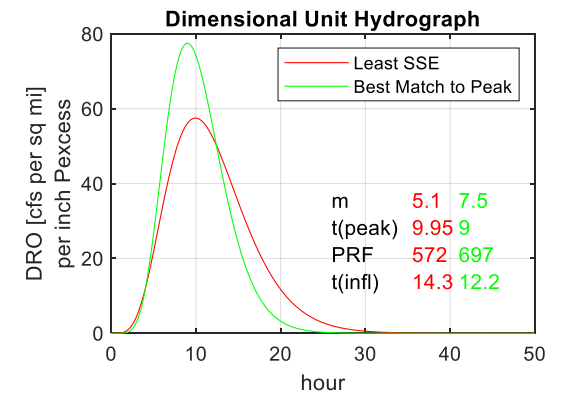
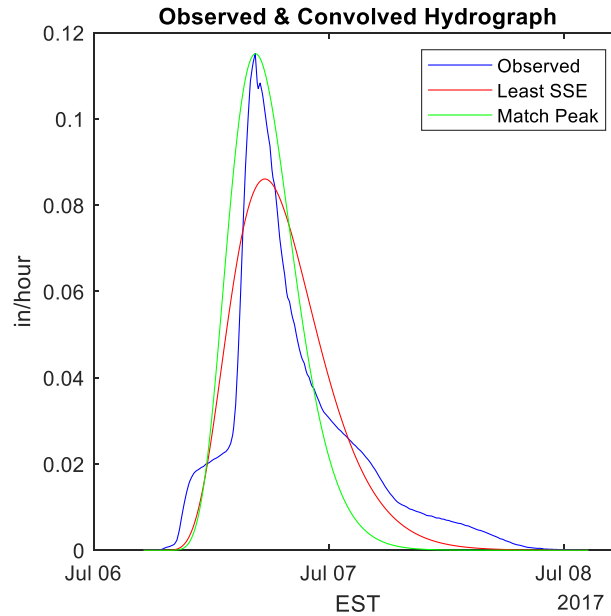
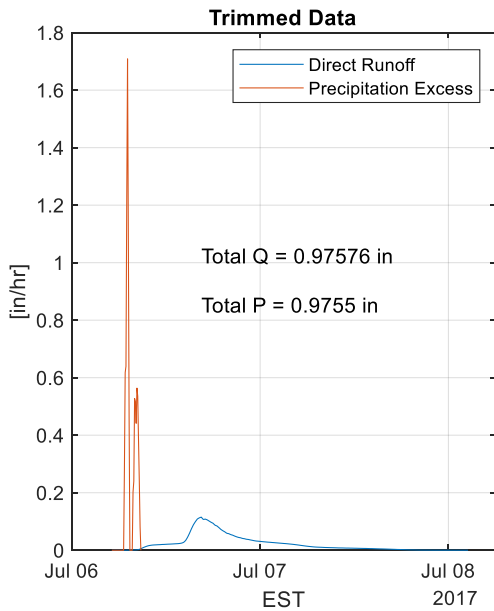
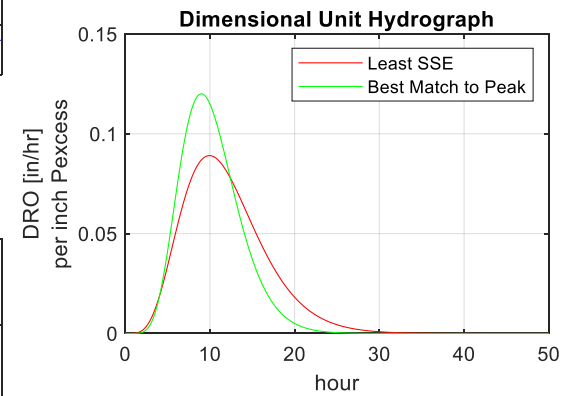
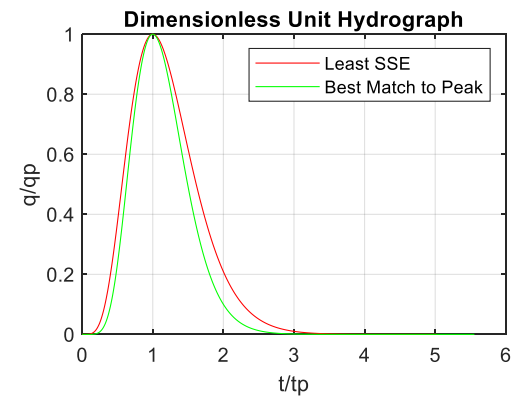
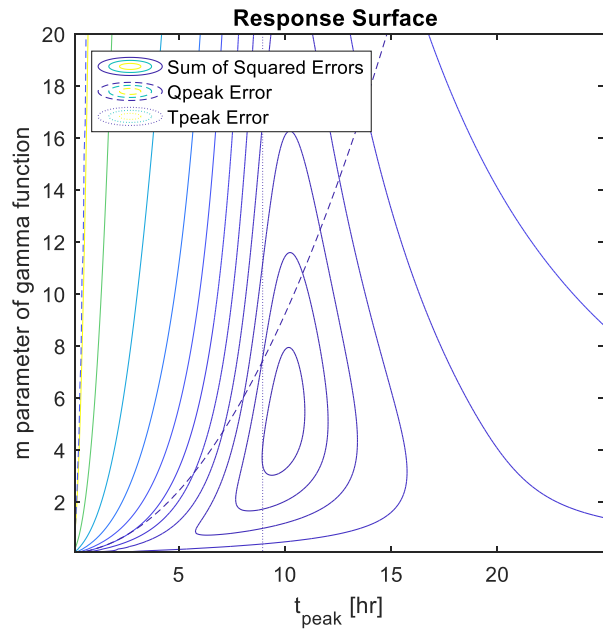
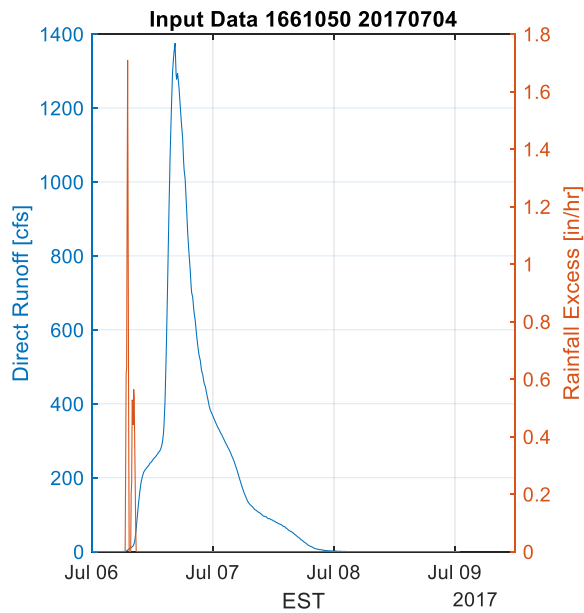












APPENDIX 2  
BASIN STATISTICS FROM GISHYDRONXT

(Watersheds with missing "Length" or "Storage" Variables  
in Hydrology Panel Report 2020, Appendix 1)

GISHydro Release Version Date: February, 2021  
Project Name: KB1483200  
Analysis Date: August 28, 2021  
Data Selected:  
DEM Coverage: NED DEM 201805  
Land Use Coverage: NLCD 2011  
Soil Coverage: SSURGO 201805  
Hydrologic Condition: Good  
Impose NHD stream Locations: Yes  
Outlet Easting: 514663 m (MD Stateplane, NAD 1983)  
Outlet Northing: 189507 m (MD Stateplane, NAD 1983)  
Findings:  
Outlet Location: Eastern Coastal Plain  
Outlet State: Maryland  
Drainage Area 4.06 square miles  
-Eastern Coastal Plain 100.00 percent of area  
  
Channel Slope: 13.49100410 feet/mile (0.00255511 feet/feet)  
Land Slope: 0.01898160 feet/feet  
Urban Area (percent): 0.5  
Impervious Area (percent): 0.8  
  
Time of Concentration: 16.82 hours [W.O. Thomas, Jr. Equation]  
Time of Concentration: 5.53 hours [From SCS Lag Equation \* 1.67]  
Longest Flow Path: 4.01 miles  
Basin Relief: 38.35 feet  
Average CN: 72.3  
Forest Cover (percent): 26.5  
Storage (percent): 21.4  
Limestone (percent): 0.0  
Selected Soils Data Statistics Percent:  
A Soils: 33.8  
B Soils: 33.0  
C Soils: 12.4  
D Soils: 20.5  
SSURGO Soils Data Statistics Percent (used in Regression Equations):  
A Soils: 33.8  
B Soils: 33.0  
C Soils: 12.4  
D Soils: 20.5  
2-Year,24-hour Prec.: 3.20 inches  
Mean Annual Prec.: 43.78 inches

GISHydro Release Version Date: February, 2021  
Project Name: My Project  
Analysis Date: August 28, 2021  
Data Selected:  
DEM Coverage: NED DEM 201805  
Land Use Coverage: NLCD 2011  
Soil Coverage: SSURGO 201805  
Hydrologic Condition: Good  
Impose NHD stream Locations: Yes  
Outlet Easting: 528940 m (MD Stateplane, NAD 1983)  
Outlet Northing: 138561 m (MD Stateplane, NAD 1983)  
Findings:  
Outlet Location: Eastern Coastal Plain  
Outlet State: Maryland  
Drainage Area 3.31 square miles  
-Eastern Coastal Plain 100.00 percent of area  
  
Channel Slope: 5.23820418 feet/mile (0.00099208 feet/feet)  
Land Slope: 0.00729976 feet/feet  
Urban Area (percent): 0.2  
Impervious Area (percent): 0.4  
  
Time of Concentration: 19.18 hours [W.O. Thomas, Jr. Equation]  
Time of Concentration: 6.61 hours [From SCS Lag Equation \* 1.67]  
Longest Flow Path: 3.62 miles  
Basin Relief: 15.50 feet  
Average CN: 79.8  
Forest Cover (percent): 12.6  
Storage (percent): 25.0  
Limestone (percent): 0.0  
Selected Soils Data Statistics Percent:  
A Soils: 30.3  
B Soils: 5.1  
C Soils: 0.0  
D Soils: 64.7  
SSURGO Soils Data Statistics Percent (used in Regression Equations):  
A Soils: 30.3  
B Soils: 5.1  
C Soils: 0.0  
D Soils: 64.7  
2-Year,24-hour Prec.: 3.36 inches  
Mean Annual Prec.: 45.04 inches

GISHydro Release Version Date: February, 2021  
Project Name: My Project  
Analysis Date: August 28, 2021  
Data Selected:  
DEM Coverage: NED DEM 201805  
Land Use Coverage: 2010 MOP  
Soil Coverage: SSURGO 201805  
Hydrologic Condition: Good  
Impose NHD stream Locations: Yes  
Outlet Easting: 491624 m (MD Stateplane, NAD 1983)  
Outlet Northing: 144877 m (MD Stateplane, NAD 1983)  
Findings:  
Outlet Location: Eastern Coastal Plain  
Outlet State: Maryland  
Drainage Area 87.64 square miles  
-Eastern Coastal Plain 100.00 percent of area  
  
Channel Slope: 3.25669128 feet/mile (0.00061680 feet/feet)  
Land Slope: 0.01188516 feet/feet  
Urban Area (percent): 2.6  
Impervious Area (percent): 1.3  
  
Time of Concentration: 28.97 hours [W.O. Thomas, Jr. Equation]  
Time of Concentration: 21.84 hours [From SCS Lag Equation \* 1.67]  
Longest Flow Path: 18.70 miles  
Basin Relief: 46.08 feet  
Average CN: 75.6  
Forest Cover (percent): 31.0  
Storage (percent): 0.1  
Limestone (percent): 0.0  
Selected Soils Data Statistics Percent:  
A Soils: 20.7  
B Soils: 22.2  
C Soils: 30.1  
D Soils: 26.8  
SSURGO Soils Data Statistics Percent (used in Regression Equations):  
A Soils: 20.7  
B Soils: 22.2  
C Soils: 30.1  
D Soils: 26.8  
2-Year,24-hour Prec.: 3.25 inches  
Mean Annual Prec.: 44.17 inches

GISHydro Release Version Date: February, 2021  
Project Name: KB1493112  
Analysis Date: August 28, 2021  
Data Selected:  
DEM Coverage: NED DEM 201805  
Land Use Coverage: 2010 MOP  
Soil Coverage: SSURGO 201805  
Hydrologic Condition: Good  
Impose NHD stream Locations: Yes  
Outlet Easting: 491415 m (MD Stateplane, NAD 1983)  
Outlet Northing: 177041 m (MD Stateplane, NAD 1983)

Findings:  
Outlet Location: Eastern Coastal Plain  
Outlet State: Maryland  
Drainage Area: 6.14 square miles  
-Eastern Coastal Plain 100.00 percent of area

Channel Slope: 14.54702336 feet/mile (0.00275512 feet/feet)  
Land Slope: 0.01858567 feet/feet  
Urban Area (percent): 0.6  
Impervious Area (percent): 0.4

Time of Concentration: 11.88 hours [W.O. Thomas, Jr. Equation]  
Time of Concentration: 5.68 hours [From SCS Lag Equation \* 1.67]  
Longest Flow Path: 5.11 miles  
Basin Relief: 50.01 feet  
Average CN: 78.5  
Forest Cover (percent): 7.9  
Storage (percent): 0.5  
Limestone (percent): 0.0

Selected Soils Data Statistics Percent:

A Soils: 0.2  
B Soils: 28.6  
C Soils: 65.7  
D Soils: 5.4

SSURGO Soils Data Statistics Percent (used in Regression Equations):

A Soils: 0.2  
B Soils: 28.6  
C Soils: 65.7  
D Soils: 5.4

2-Year,24-hour Prec.: 3.24 inches  
Mean Annual Prec.: 44.64 inches



GISHydro Release Version Date: February, 2021  
Project Name: My Project  
Analysis Date: August 28, 2021  
Data Selected:  
DEM Coverage: NED DEM 201805  
Land Use Coverage: 2010 MOP  
Soil Coverage: SSURGO 201805  
Hydrologic Condition: Good  
Impose NHD stream Locations: Yes  
Outlet Easting: 426882 m (MD Stateplane, NAD 1983)  
Outlet Northing: 201372 m (MD Stateplane, NAD 1983)

Findings:  
Outlet Location: Piedmont  
Outlet State: Maryland  
Drainage Area 0.14 square miles  
-Piedmont 100.00 percent of area

Channel Slope: 190.26297335 feet/mile (0.03603465 feet/feet)  
Land Slope: 0.10482415 feet/feet  
Urban Area (percent): 0.0  
Impervious Area (percent): 0.0

Time of Concentration: 2.28 hours [W.O. Thomas, Jr. Equation]  
Time of Concentration: 0.84 hours [From SCS Lag Equation \* 1.67]  
Longest Flow Path: 0.73 miles  
Basin Relief: 99.27 feet  
Average CN: 59.4  
Forest Cover (percent): 100.0  
Storage (percent): 0.0  
Limestone (percent): 0.0

Selected Soils Data Statistics Percent:

A Soils: 0.0  
B Soils: 75.6  
C Soils: 13.1  
D Soils: 11.3

SSURGO Soils Data Statistics Percent (used in Regression Equations):

A Soils: 0.0  
B Soils: 75.6  
C Soils: 13.1  
D Soils: 11.3

2-Year,24-hour Prec.: 3.29 inches  
Mean Annual Prec.: 46.65 inches

GISHydro Release Version Date: February, 2021  
Project Name: KB1585090  
Analysis Date: August 28, 2021  
Data Selected:  
DEM Coverage: NED DEM 201805  
Land Use Coverage: 2010 MOP  
Soil Coverage: SSURGO 201805  
Hydrologic Condition: Good  
Impose NHD stream Locations: Yes  
Outlet Easting: 443440 m (MD Stateplane, NAD 1983)  
Outlet Northing: 190278 m (MD Stateplane, NAD 1983)

Findings:  
Outlet Location: Western Coastal Plain  
Outlet State: Maryland  
Drainage Area 2.64 square miles  
-Piedmont 78.38 percent of area  
-Western Coastal Plain 21.62 percent of area

Channel Slope: 80.56496106 feet/mile (0.01525852 feet/feet)  
Land Slope: 0.07127592 feet/feet  
Urban Area (percent): 78.4  
Impervious Area (percent): 46.7

\*\*\*\*\*  
Watershed is within 5km of physiographic  
province boundary. You should consider  
sensitivity of discharges to region location.  
\*\*\*\*\*

Time of Concentration: 2.16 hours [W.O. Thomas, Jr. Equation]  
Time of Concentration: 1.63 hours [From SCS Lag Equation \* 1.67]  
Longest Flow Path: 3.31 miles  
Basin Relief: 170.22 feet  
Average CN: 85.5  
Forest Cover (percent): 9.9  
Storage (percent): 0.0  
Limestone (percent): 0.0  
Selected Soils Data Statistics Percent:  
A Soils: 0.0  
B Soils: 5.2  
C Soils: 45.0  
D Soils: 49.8  
SSURGO Soils Data Statistics Percent (used in Regression Equations):  
A Soils: 0.0  
B Soils: 5.2  
C Soils: 45.0  
D Soils: 49.8  
2-Year,24-hour Prec.: 3.37 inches  
Mean Annual Prec.: 49.62 inches

GISHydro Release Version Date: February, 2021  
 Project Name: My Project  
 Analysis Date: August 28, 2021  
 Data Selected:  
   DEM Coverage: NED DEM 201805  
   Land Use Coverage: 2010 MOP  
   Soil Coverage: SSURGO 201805  
   Hydrologic Condition: Good  
   Impose NHD stream Locations: Yes  
   Outlet Easting: 448874 m (MD Stateplane, NAD 1983)  
   Outlet Northing: 190665 m (MD Stateplane, NAD 1983)

Findings:  
   Outlet Location: Western Coastal Plain  
   Outlet State: Maryland  
   Drainage Area: 2.45 square miles  
     -Piedmont 30.56 percent of area  
     -Western Coastal Plain 69.44 percent of area

Channel Slope: 71.98719869 feet/mile (0.01363394 feet/feet)  
 Land Slope: 0.05599917 feet/feet  
 Urban Area (percent): 40.4  
 Impervious Area (percent): 22.1

\*\*\*\*\*  
   Watershed is within 5km of physiographic  
   province boundary. You should consider  
   sensitivity of discharges to region location.  
 \*\*\*\*\*

Time of Concentration: 4.76 hours [W.O. Thomas, Jr. Equation]  
 Time of Concentration: 2.26 hours [From SCS Lag Equation \* 1.67]  
 Longest Flow Path: 3.39 miles  
 Basin Relief: 142.61 feet  
 Average CN: 79.8  
 Forest Cover (percent): 29.1  
 Storage (percent): 0.0  
 Limestone (percent): 0.0  
 Selected Soils Data Statistics Percent:  
   A Soils: 2.1  
   B Soils: 13.0  
   C Soils: 50.0  
   D Soils: 35.0  
 SSURGO Soils Data Statistics Percent (used in Regression Equations):  
   A Soils: 2.1  
   B Soils: 13.0  
   C Soils: 50.0  
   D Soils: 35.0  
 2-Year,24-hour Prec.: 3.34 inches  
 Mean Annual Prec.: 48.37 inches

GISHydro Release Version Date: February, 2021  
Project Name: KB1585230  
Analysis Date: August 28, 2021  
Data Selected:  
DEM Coverage: NED DEM 201805  
Land Use Coverage: 2010 MOP  
Soil Coverage: SSURGO 201805  
Hydrologic Condition: Good  
Impose NHD stream Locations: Yes  
Outlet Easting: 440082 m (MD Stateplane, NAD 1983)  
Outlet Northing: 184792 m (MD Stateplane, NAD 1983)

Findings:  
Outlet Location: Western Coastal Plain  
Outlet State: Maryland  
Drainage Area 3.48 square miles  
-Piedmont 21.86 percent of area  
-Western Coastal Plain 78.14 percent of area

Channel Slope: 79.29394052 feet/mile (0.01501779 feet/feet)  
Land Slope: 0.05014206 feet/feet  
Urban Area (percent): 90.6  
Impervious Area (percent): 45.4

\*\*\*\*\*  
Watershed is within 5km of physiographic  
province boundary. You should consider  
sensitivity of discharges to region location.  
\*\*\*\*\*

Time of Concentration: 3.69 hours [W.O. Thomas, Jr. Equation]  
Time of Concentration: 2.15 hours [From SCS Lag Equation \* 1.67]  
Longest Flow Path: 3.80 miles  
Basin Relief: 183.76 feet  
Average CN: 85.8  
Forest Cover (percent): 1.8  
Storage (percent): 0.0  
Limestone (percent): 0.0  
Selected Soils Data Statistics Percent:  
A Soils: 1.5  
B Soils: 11.1  
C Soils: 24.8  
D Soils: 62.6  
SSURGO Soils Data Statistics Percent (used in Regression Equations):  
A Soils: 1.5  
B Soils: 11.1  
C Soils: 24.8  
D Soils: 62.6  
2-Year,24-hour Prec.: 3.34 inches  
Mean Annual Prec.: 47.68 inches

GISHydro Release Version Date: February, 2021  
Project Name: KB1644371  
Analysis Date: August 28, 2021  
Data Selected:  
DEM Coverage: NED DEM 201805  
Land Use Coverage: 2010 MOP  
Soil Coverage: SSURGO 201805  
Hydrologic Condition: Good  
Impose NHD stream Locations: Yes  
Outlet Easting: 377919 m (MD Stateplane, NAD 1983)  
Outlet Northing: 173718 m (MD Stateplane, NAD 1983)

Findings:  
Outlet Location: Piedmont  
Outlet State: Maryland  
Drainage Area 0.47 square miles  
-Piedmont 100.00 percent of area

Channel Slope: 116.82425413 feet/mile (0.02212581 feet/feet)  
Land Slope: 0.07780400 feet/feet  
Urban Area (percent): 55.5  
Impervious Area (percent): 27.5

Time of Concentration: 1.35 hours [W.O. Thomas, Jr. Equation]  
Time of Concentration: 0.97 hours [From SCS Lag Equation \* 1.67]  
Longest Flow Path: 1.32 miles  
Basin Relief: 99.45 feet  
Average CN: 77.3  
Forest Cover (percent): 24.0  
Storage (percent): 0.0  
Limestone (percent): 0.0

Selected Soils Data Statistics Percent:

A Soils: 0.0  
B Soils: 54.8  
C Soils: 32.5  
D Soils: 12.7

SSURGO Soils Data Statistics Percent (used in Regression Equations):

A Soils: 0.0  
B Soils: 54.8  
C Soils: 32.5  
D Soils: 12.7

2-Year,24-hour Prec.: 3.08 inches  
Mean Annual Prec.: 42.56 inches

GISHydro Release Version Date: February, 2021  
Project Name: My Project  
Analysis Date: August 28, 2021  
Data Selected:  
DEM Coverage: NED DEM 201805  
Land Use Coverage: 2010 MOP  
Soil Coverage: SSURGO 201805  
Hydrologic Condition: Good  
Impose NHD stream Locations: Yes  
Outlet Easting: 376153 m (MD Stateplane, NAD 1983)  
Outlet Northing: 170143 m (MD Stateplane, NAD 1983)

Findings:  
Outlet Location: Piedmont  
Outlet State: Maryland  
Drainage Area: 1.23 square miles  
-Piedmont 100.00 percent of area

Channel Slope: 63.88346191 feet/mile (0.01209914 feet/feet)  
Land Slope: 0.04769627 feet/feet  
Urban Area (percent): 67.7  
Impervious Area (percent): 53.4

Time of Concentration: 1.39 hours [W.O. Thomas, Jr. Equation]  
Time of Concentration: 1.73 hours [From SCS Lag Equation \* 1.67]  
Longest Flow Path: 2.45 miles  
Basin Relief: 73.06 feet  
Average CN: 82.6  
Forest Cover (percent): 9.9  
Storage (percent): 0.1  
Limestone (percent): 0.0

Selected Soils Data Statistics Percent:

A Soils: 0.0  
B Soils: 83.2  
C Soils: 6.7  
D Soils: 10.0

SSURGO Soils Data Statistics Percent (used in Regression Equations):

A Soils: 0.0  
B Soils: 83.2  
C Soils: 6.7  
D Soils: 10.0

2-Year,24-hour Prec.: 3.08 inches  
Mean Annual Prec.: 42.44 inches

GISHydro Release Version Date: February, 2021  
Project Name: My Project  
Analysis Date: August 28, 2021  
Data Selected:  
DEM Coverage: NED DEM 201805  
Land Use Coverage: 2010 MOP  
Soil Coverage: SSURGO 201805  
Hydrologic Condition: Good  
Impose NHD stream Locations: Yes  
Outlet Easting: 556120 m (MD Stateplane, NAD 1983)  
Outlet Northing: 84016 m (MD Stateplane, NAD 1983)

Findings:  
Outlet Location: Eastern Coastal Plain  
Outlet State: Maryland  
Drainage Area: 5.25 square miles  
-Eastern Coastal Plain 100.00 percent of area

Channel Slope: 7.91528944 feet/mile (0.00149911 feet/feet)  
Land Slope: 0.00847407 feet/feet  
Urban Area (percent): 4.3  
Impervious Area (percent): 3.2

Time of Concentration: 12.95 hours [W.O. Thomas, Jr. Equation]  
Time of Concentration: 9.25 hours [From SCS Lag Equation \* 1.67]  
Longest Flow Path: 5.01 miles  
Basin Relief: 27.57 feet  
Average CN: 74.7  
Forest Cover (percent): 41.4  
Storage (percent): 0.0  
Limestone (percent): 0.0

Selected Soils Data Statistics Percent:

A Soils: 28.3  
B Soils: 10.7  
C Soils: 21.0  
D Soils: 40.0

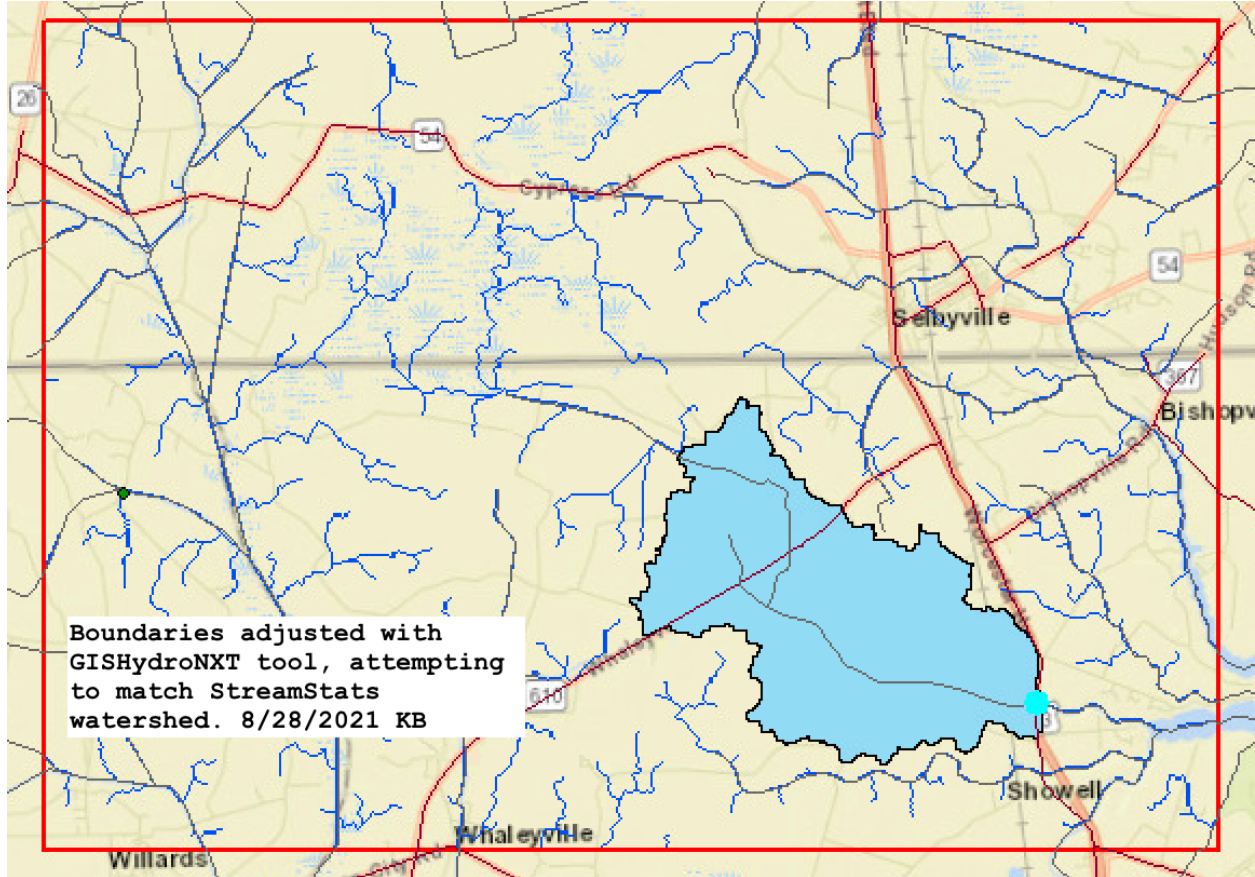
SSURGO Soils Data Statistics Percent (used in Regression Equations):

A Soils: 28.3  
B Soils: 10.7  
C Soils: 21.0  
D Soils: 40.0

2-Year,24-hour Prec.: 3.43 inches  
Mean Annual Prec.: 45.63 inches

Watershed 148471320 Birch Branch at Showell, MD

This watershed lies in the Eastern Coastal Plain on the Delmarva Peninsula. GISHydroNXT's watershed delineation in this location is unreliable due to the coarse (30-m pixel) representation of very flat terrain. GISHydroNXT's "Adjust Boundaries" tool was used to force the delineated watershed into agreement with that reported by USGS StreamStats (next page). The Basin Statistics reported on the previous page correspond to the watershed delineation shown here.

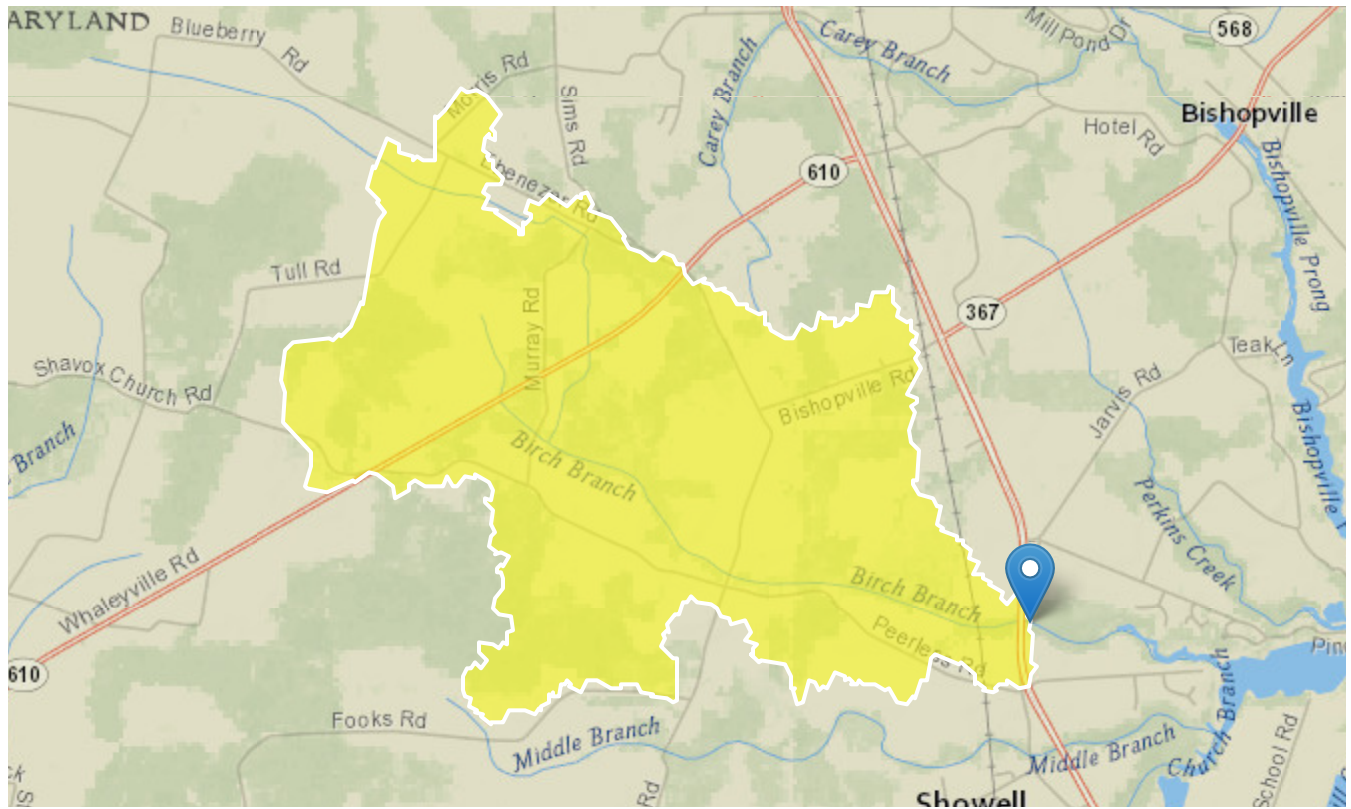


StreamStats enforces the boundaries in the Watershed Boundary Dataset included in the National Hydrography Dataset Plus (NHDPlus, <https://pubs.er.usgs.gov/publication/ofr20191096> ).



# StreamStats Report

Region ID: MD  
 Workspace ID: MD20210828174423117000  
 Clicked Point (Latitude, Longitude): 38.40938, -75.21206  
 Time: 2021-08-28 13:44:47 -0400



USGS 148471320 Birch Branch at Sowell MD, for reference in delineating watershed in GISHydroNXT.

## Basin Characteristics

Parameter Code	Parameter Description	Value	Unit
ADJCOEFF	Coefficient to adjust estimates for percentage of carbonate rock in Western Maryland	0	dimensionless
BSLDEM10ff	Mean basin slope computed from 10 m DEM in feet per foot	0.00607	foot per foot
DRNAREA	Area that drains to a point on a stream	5.19	square miles
FOREST	Percentage of area covered by forest	40.4	percent

<b>Parameter Code</b>	<b>Parameter Description</b>	<b>Value</b>	<b>Unit</b>
FOREST_MD	Percent forest from Maryland 2010 land-use data	42.2	percent
IMPERV	Percentage of impervious area	3.33	percent
LC11DEV	Percentage of developed (urban) land from NLCD 2011 classes 21-24	6.14	percent
LC11IMP	Average percentage of impervious area determined from NLCD 2011 impervious dataset	0.79	percent
LIME	Percentage of area of limestone geology	0	percent
PRECIP	Mean Annual Precipitation	44.8	inches
SOILCorD	Percentage of area of Hydrologic Soil Type C or D from SSURGO	64.5	percent
SSURGOA	Percentage of area of Hydrologic Soil Type A from SSURGO	12.2	percent
STATSGOA	Percentage of area of Hydrologic Soil Type A from STATSGO	8.7	percent
STATSGOD	Percentage of area of Hydrologic Soil Type D from STATSGO	7.43	percent

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Application Version: 4.6.2

StreamStats Services Version: 1.2.22

NSS Services Version: 2.1.2

APPENDIX 3  
BASIN STATISTICS FROM GISHYDRONXT

(Watersheds that are not included in Hydrology Panel Report  
2020, Appendix 1)

GISHydro Release Version Date: February, 2021  
Project Name: KB1486500  
Analysis Date: August 01, 2021  
Data Selected:  
DEM Coverage: NED DEM 201805  
Land Use Coverage: 2010 MOP  
Soil Coverage: SSURGO 201805  
Hydrologic Condition: Good  
Impose NHD stream Locations: Yes  
Outlet Easting: 525011 m (MD Stateplane, NAD 1983)  
Outlet Northing: 76995 m (MD Stateplane, NAD 1983)

Findings:  
Outlet Location: Eastern Coastal Plain  
Outlet State: Maryland  
Drainage Area 11.18 square miles  
-Eastern Coastal Plain 100.00 percent of area

Channel Slope: 6.35401010 feet/mile (0.00120341 feet/feet)  
Land Slope: 0.01286013 feet/feet  
Urban Area (percent): 25.7  
Impervious Area (percent): 16.2

\*\*\*\*\*  
IMPERVIOUS AREA IN WATERSHED EXCEEDS 10%.  
Calculated discharges from Fixed Region  
Regression Equations may not be appropriate.  
\*\*\*\*\*

Time of Concentration: 14.96 hours [W.O. Thomas, Jr. Equation]  
Time of Concentration: 10.65 hours [From SCS Lag Equation \* 1.67]  
Longest Flow Path: 6.23 miles  
Basin Relief: 25.31 feet  
Average CN: 68.4  
Forest Cover (percent): 35.4  
Storage (percent): 1.4  
Limestone (percent): 0.0  
Selected Soils Data Statistics Percent:  
A Soils: 50.0  
B Soils: 0.5  
C Soils: 4.9  
D Soils: 43.2  
SSURGO Soils Data Statistics Percent (used in Regression Equations):  
A Soils: 50.0  
B Soils: 0.5  
C Soils: 4.9  
D Soils: 43.2  
2-Year,24-hour Prec.: 3.46 inches  
Mean Annual Prec.: 46.08 inches

GISHydro Release Version Date: February, 2021  
Project Name: KB1581757  
Analysis Date: August 28, 2021  
Data Selected:

DEM Coverage:  
Land Use Coverage: 2010 MOP  
Soil Coverage: SSURGO 201805  
Hydrologic Condition: Good  
Impose NHD stream Locations: Yes  
Outlet Easting: 459683 m (MD Stateplane, NAD 1983)  
Outlet Northing: 197033 m (MD Stateplane, NAD 1983)

Findings:

Outlet Location: Western Coastal Plain  
Outlet State: Maryland  
Drainage Area 55.85 square miles  
-Piedmont 95.08 percent of area  
-Western Coastal Plain 4.92 percent of area

Channel Slope: 27.27076896 feet/mile (0.00516492 feet/feet)  
Land Slope: 0.08477213 feet/feet  
Urban Area (percent): 40.2  
Impervious Area (percent): 17.8

\*\*\*\*\*  
Watershed is within 5km of physiographic  
province boundary. You should consider  
sensitivity of discharges to region location.  
\*\*\*\*\*

Time of Concentration: 8.97 hours [W.O. Thomas, Jr. Equation]  
Time of Concentration: 11.87 hours [From SCS Lag Equation \* 1.67]  
Longest Flow Path: 25.87 miles  
Basin Relief: 382.91 feet  
Average CN: 71.6  
Forest Cover (percent): 27.0  
Storage (percent): 0.2  
Limestone (percent): 0.0  
Selected Soils Data Statistics Percent:  
A Soils: 1.7  
B Soils: 67.9  
C Soils: 18.5  
D Soils: 11.7  
SSURGO Soils Data Statistics Percent (used in Regression Equations):  
A Soils: 1.7  
B Soils: 67.9  
C Soils: 18.5  
D Soils: 11.7  
2-Year,24-hour Prec.: 3.30 inches  
Mean Annual Prec.: 47.99 inches

GISHydro Release Version Date: February, 2021  
 Project Name: My Project  
 Analysis Date: August 28, 2021  
 Data Selected:  
   DEM Coverage: NED DEM 201805  
   Land Use Coverage: NLCD 2011  
   Soil Coverage: SSURGO 201805  
   Hydrologic Condition: Good  
   Impose NHD stream Locations: Yes  
   Outlet Easting: 381046 m (MD Stateplane, NAD 1983)  
   Outlet Northing: 221379 m (MD Stateplane, NAD 1983)

Findings:  
   Outlet Location: Blue Ridge and Great Valley  
   Outlet State: Maryland  
   Drainage Area: 31.37 square miles  
     -Piedmont 21.52 percent of area  
     -Blue Ridge and Great Valley 78.48 percent of area

Channel Slope: 17.80400682 feet/mile (0.00337197 feet/feet)  
 Land Slope: 0.04839904 feet/feet  
 Urban Area (percent): 5.5  
 Impervious Area (percent): 2.5

\*\*\*\*\*  
   Watershed is within 5km of physiographic  
   province boundary. You should consider  
   sensitivity of discharges to region location.  
 \*\*\*\*\*

\*\*\*\*\*  
   Watershed is within 1km of underlying limestone  
   geology. You should consider sensitivity  
   of discharges to percent limestone calculated.  
 \*\*\*\*\*

Time of Concentration: 9.56 hours [W.O. Thomas, Jr. Equation]  
 Time of Concentration: 9.98 hours [From SCS Lag Equation \* 1.67]  
 Longest Flow Path: 16.76 miles  
 Basin Relief: 180.71 feet  
 Average CN: 75.4  
 Forest Cover (percent): 15.1  
 Storage (percent): 1.9  
 Limestone (percent): 2.5  
 Selected Soils Data Statistics Percent:  
   A Soils: 0.5  
   B Soils: 48.3  
   C Soils: 23.0  
   D Soils: 27.9  
 SSURGO Soils Data Statistics Percent (used in Regression Equations):  
   A Soils: 0.5  
   B Soils: 48.3  
   C Soils: 23.0  
   D Soils: 27.9  
 2-Year,24-hour Prec.: 3.01 inches  
 Mean Annual Prec.: 42.73 inches

GISHydro Release Version Date: February, 2021  
Project Name: KB1644372  
Analysis Date: August 28, 2021  
Data Selected:  
DEM Coverage: NED DEM 201805  
Land Use Coverage: 2010 MOP  
Soil Coverage: SSURGO 201805  
Hydrologic Condition: Good  
Impose NHD stream Locations: Yes  
Outlet Easting: 378438 m (MD Stateplane, NAD 1983)  
Outlet Northing: 172752 m (MD Stateplane, NAD 1983)

Findings:  
Outlet Location: Piedmont  
Outlet State: Maryland  
Drainage Area 0.34 square miles  
-Piedmont 100.00 percent of area

Channel Slope: 112.77474476 feet/mile (0.02135885 feet/feet)  
Land Slope: 0.06069387 feet/feet  
Urban Area (percent): 6.1  
Impervious Area (percent): 1.6

Time of Concentration: 1.74 hours [W.O. Thomas, Jr. Equation]  
Time of Concentration: 0.99 hours [From SCS Lag Equation \* 1.67]  
Longest Flow Path: 1.26 miles  
Basin Relief: 81.09 feet  
Average CN: 79.6  
Forest Cover (percent): 28.8  
Storage (percent): 0.0  
Limestone (percent): 0.0

Selected Soils Data Statistics Percent:

A Soils: 0.0  
B Soils: 17.1  
C Soils: 74.4  
D Soils: 8.5

SSURGO Soils Data Statistics Percent (used in Regression Equations):

A Soils: 0.0  
B Soils: 17.1  
C Soils: 74.4  
D Soils: 8.5

2-Year,24-hour Prec.: 3.09 inches  
Mean Annual Prec.: 42.66 inches