

# Flood Operation Rules for a Single Reservoir

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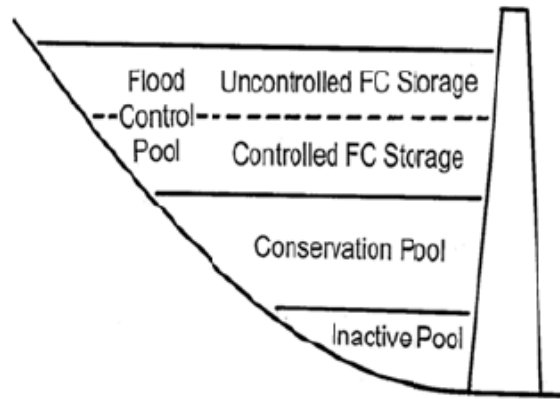
## Abstract

This paper examines the theoretical behavior of regulated peak transforms by different reservoir operation rules. Four rules are used to simulate inflow, outflow, and storage within the reservoir and illustrate the development of a peak flow transform. These rules are: 1) optimal peak reduction with perfect foreknowledge of the flood hydrograph; 2) minimized exceedences of downstream channel capacity; 3) maximum peak flow reduction rule with incomplete forecasts; and 4) least exceedence probability rule with reoperation and incomplete forecasts. The latter two operation rules with incomplete foreknowledge of the flood hydrograph are likely to work better in a hydrograph with steep or abrupt limbs.

## 1. Reservoir Operation and Reoperation

A reservoir operation plan is a set of rules establishing the quantities of water to be stored, released, or withdrawn from a reservoir or system of reservoirs under various conditions [Wurbs, 1993]. Based on a reservoir plan, reservoir operation decisions include managing the consequences and hazard of reservoir storage and flood control, regulating reservoir storage and outflow among water users, generating electricity use, allocating land and environmental resources, and other beneficial concerns. In general, the purpose of reservoir operation is to balance the conflicts between filling water storage for conservation uses and emptying the volume for flood regulation use.

Illustrated in Fig 1.1, a reservoir can be divided into several different layers or pools. Commonly in a reservoir operation plan, a reservoir can be divided into an inactive pool, a buffer pool, a conservation water supply pool, and flood pool (Wurbs 1993). The conservation pool can serve urban and agriculture water supply, hydropower and recreation. The flood control pool is for flood protection. Based on the function of the pools, a reservoir can be used for water supply or flood protection solely, or a combination of uses.



**Fig 1.1 Reservoir Storage Allocation Pools [Ford, 1990]**

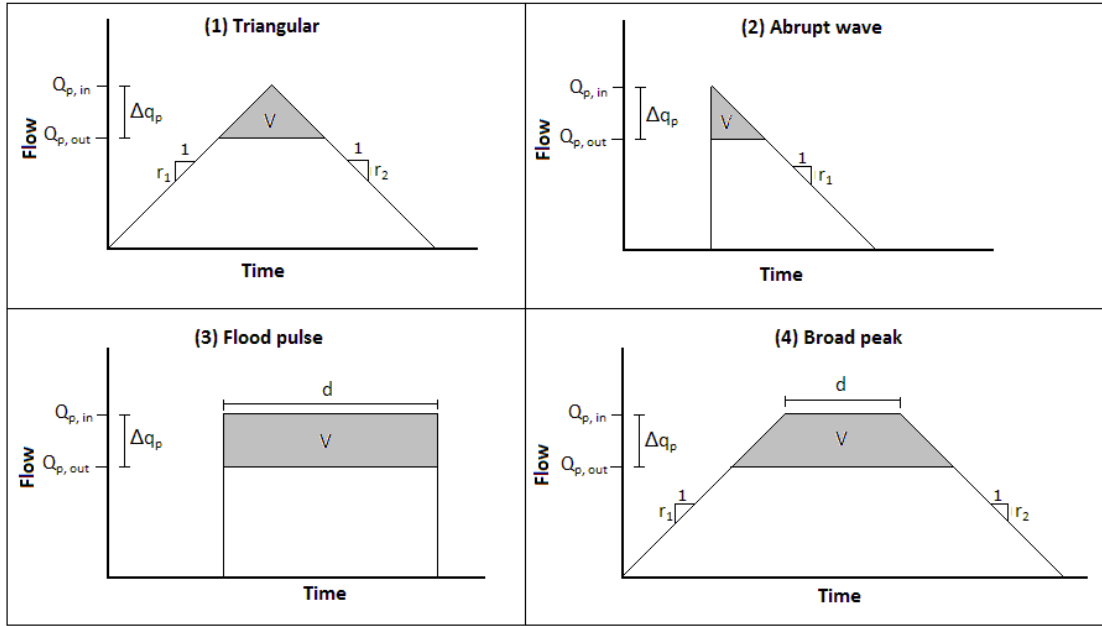
Reservoir reoperation changes established water control policies or rules to improve water-control management (Ji, 2011). Sometimes, established water control policies or rules cannot meet the original water control purpose or accommodate newer purposes. A typical reservoir reoperation is to change operation rules which reallocate storage capacity between the flood control and conservation pools, by adjusting the elevation of the top of the conservation pool (the bottom of the flood control pool).

Johnson (1990) and Duren (1971) examined storage reallocation to accommodate new water supply demand, hydropower and flood control. Ji (2011) discussed estimation methods for regulated flow frequency for major flood control reservoirs with reallocation of reservoir flood storage. Richter (2006) brought more concern for environmental flows downstream of dams, with new ideas about restoring floodplains to benefit downstream ecosystems.

## 2. Simple Inflow Hydrographs

Three main factors affect the reservoir's inflow flood volume and peak outflow (Ergish, 2010): 1) inflow hydrograph volume and shape; 2) controllable reservoir storage capacity; 3) reservoir operation rules and constraints. Reservoir operation rules and constraints are commonly fixed, and the controllable reservoir storage capacity is constant. Theoretically, different hydrograph shapes and volumes will dominate the inflow and outflow relationship.

As illustrated in Fig 2.1, four basic simple inflow hydrographs are explored: 1) simple triangular shape hydrograph with linear rise and recession; 2) an abrupt flood wave followed by a linear recession; 3) a rectangular pulse flood wave; and 4) trapezoidal hydrograph with an extended peak between the rising and recession limbs. The parameters of each hydrograph are peak inflow ( $Q_{p,in}$ ), available reservoir storage volume ( $V$ ), slope of the rising and receding limbs ( $r_1, r_2$ ), and duration of the peak ( $d$ ). Based on hydrograph attributes, the given controllable reservoir storage capacity, and reservoir operation rules, we can formulate the peak outflow.



**Fig 2.1 Four Basic Hydrographs (Ergish, 2010)**

## 2.1 Derivation

Ergish (2010) derived the general numerical expression of the four types of hydrographs. As illustrated in Fig 2.1, based on the hydrograph shapes and the parameters peak inflow ( $Q_{p,in}$ ), storage volume ( $V$ ), slopes of the rising and receding limbs ( $r_1, r_2$ ), and duration of the peak ( $d$ ), the formula of the peak outflow  $Q_{p,out}$  can be achieved.

Triangular, Hydrograph 1:

$$\Delta q_p = Q_{p,in} - Q_{p,out}$$

$$V = \frac{\Delta q_p^2}{2r_1} + \frac{\Delta q_p^2}{2r_2}$$

$$\Delta q_p = \sqrt{\frac{2Vr_1r_2}{r_1 + r_2}}$$

$$\therefore Q_{p,out} = Q_{p,in} - \sqrt{\frac{2Vr_1r_2}{r_1 + r_2}} \quad (1)$$

Abrupt wave, Hydrograph 2:

$$\Delta q_p = Q_{p,in} - Q_{p,out}$$

$$V = \frac{\Delta q_p^2}{2r}$$

$$\Delta q_p = \sqrt{2Vr}$$

$$\therefore Q_{p,out} = Q_{p,in} - \sqrt{2Vr} \quad (2)$$

Flood pulse, Hydrograph 3:

$$\Delta q_p = Q_{p,in} - Q_{p,out}$$

$$V = d\Delta q_p$$

$$\Delta q_p = \frac{V}{d}$$

$$\therefore Q_{p,out} = Q_{p,in} - \frac{V}{d} \quad (3)$$

Broad peak, Hydrograph 4:

$$\Delta q_p = Q_{p,in} - Q_{p,out}$$

$$V = \frac{\Delta q_p^2}{2r_1} + \frac{\Delta q_p^2}{2r_2} + d\Delta q_p$$

$$\Delta q_p = \frac{-d \pm \sqrt{d^2 - 2(r_1 + r_2)(-V)}}{r_1 + r_2}$$

$$\therefore Q_{p,out} = Q_{p,in} - \frac{-d \pm \sqrt{d^2 - 2(r_1 + r_2)(-V)}}{r_1 + r_2} \quad (4)$$

From the shape of the four hydrographs, if we increase the slope of  $r_1$  and  $r_2$ , triangular hydrographs will become pulse hydrographs; if we change the duration of the broad peak to 0, the broad peak hydrographs become triangular hydrographs. We can also derive it from the numerical formula.

Since the storage volume for broad peak hydrographs is:

$$V = \frac{r_1 + r_2}{2r_1r_2} \Delta q_p^2 + d\Delta q_p$$

If the duration time  $d=0$ , the formula for  $V$  is the same for triangular hydrographs. If the slope  $r_1$  and  $r_2$  are very steep, approximating a pulse flow, the former term becomes negligible and the formula is the same for rectangle shape hydrograph. So the trapezoidal hydrographs formula is the general solution of the four types of hydrographs (Ergish, 2010).

### 3. Maximum Peak Flow Reduction Rule

For maximum peak outflow reduction, available storage within the reservoir is allocated to store the inflow peak and the inflow exceeds the calculated  $Q_{p,out}$  from the equations above. This requires foreknowledge of the inflow hydrograph. Storage in the reservoir is simply the remainder of inflow not released as outflow.

Consulting a similar work done by Ergish (2010), each type of the four different hydrographs was examined over a range of flood volumes. A reservoir with a flood pool capacity of 3,000 CF and  $r_1=r_2=8$  cfd/hr are used for theoretical derivation and illustration. Each plot shows the inflow, outflow and the reservoir storage volume.

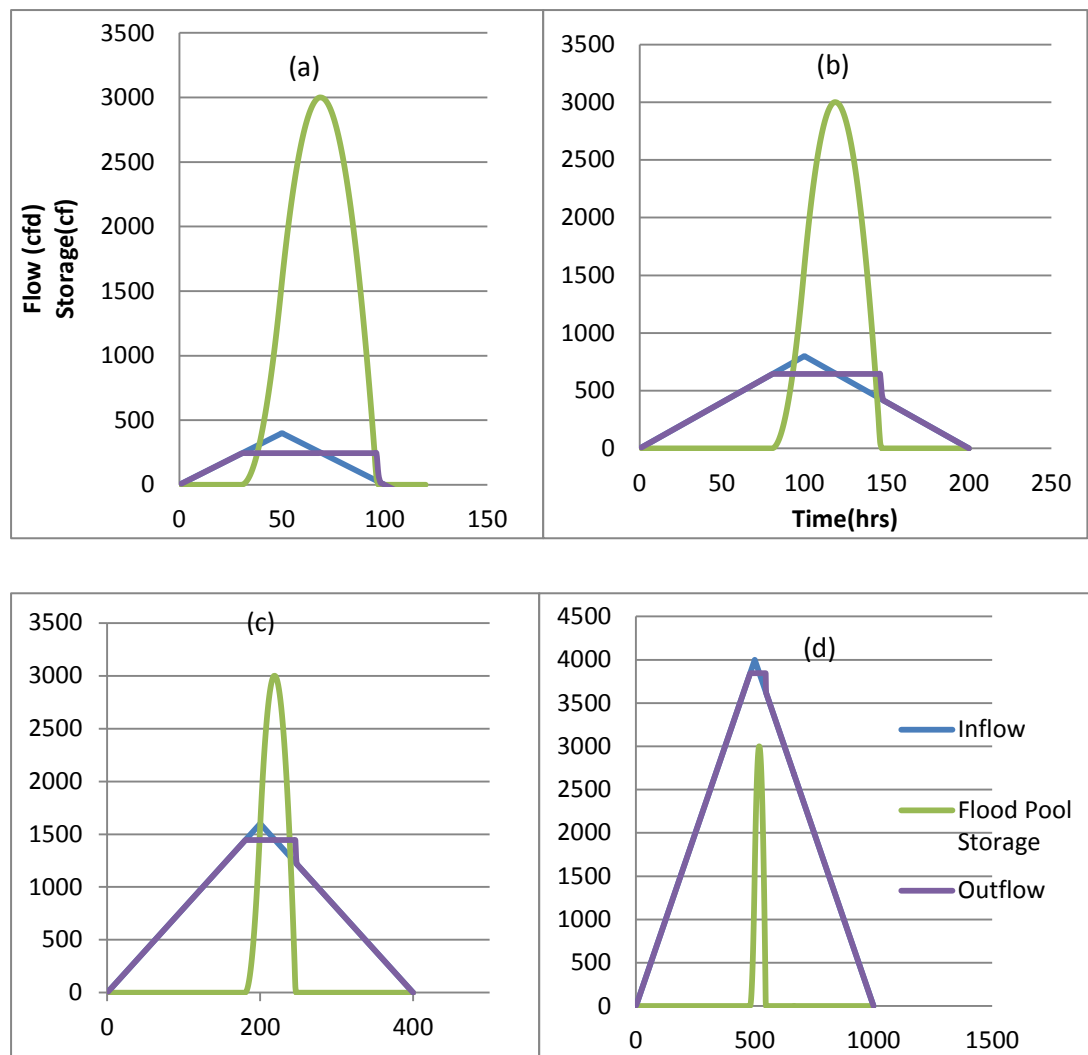


Fig 3.1 Inflow-outflow-storage plot for triangular hydrograph 1 with Maximum Peak Reduction Rule, inflow hydrograph durations were a) 100 hours, b) 200 hours, c) 400 hours, and d) 1000 hours

Figure 3.1 shows how a reservoir would operate in the Maximum Peak Reduction Rule. As visualized in the figure, this operation rule cuts the inflow peak and stores the peak to the latter time period, making the peak flatter and longer. Figure 3.1 a-d shows how the flood pool storage and outflow changes with the increase of inflow.

The slopes of the triangular hydrographs were held constant and the duration time increases from figures a to d. Figure 3.1.a-d shows peak-minimizing operation in which the outflow is equal to the inflow until the inflow reaches the optimal reduction point. From this point, the flood pool starts to store flow and the outflow remains constant, which means that the reservoir can optimally capture the peak with a known flood forecast. In Figure 3.1 d, the flood is too large and the reservoir becomes less effective to capture the peak flow, in which the outflow almost equals to inflow.

Figure 3.2 illustrates how the reservoir will operate in an abrupt hydrograph. The durations of the storms are determined for visualized purpose. An abrupt hydrograph has a sudden increase in the beginning of the storm, which means the reservoir will capture the peak flow when the storm begins. The plot is similar to plot 3.1 except the reduction point comes earlier in the beginning of the storm. From this point, the flood pool starts to store flow and the outflow remains constant. After the early storing period, the outflow equals the inflow. Figure 3.2 a-c shows significant capture of the peak flow while figure 3.2 d shows a situation where the immense storm only allows a small reduction of the peak.

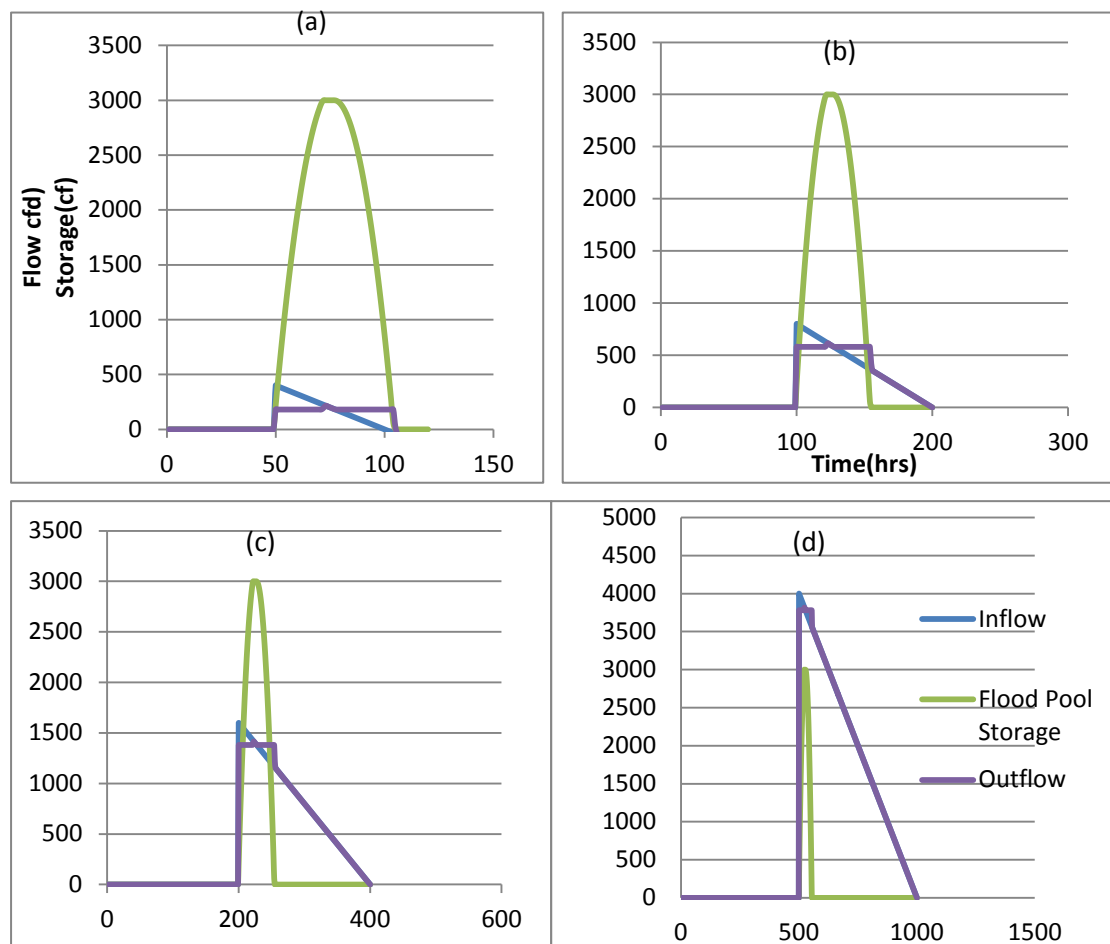
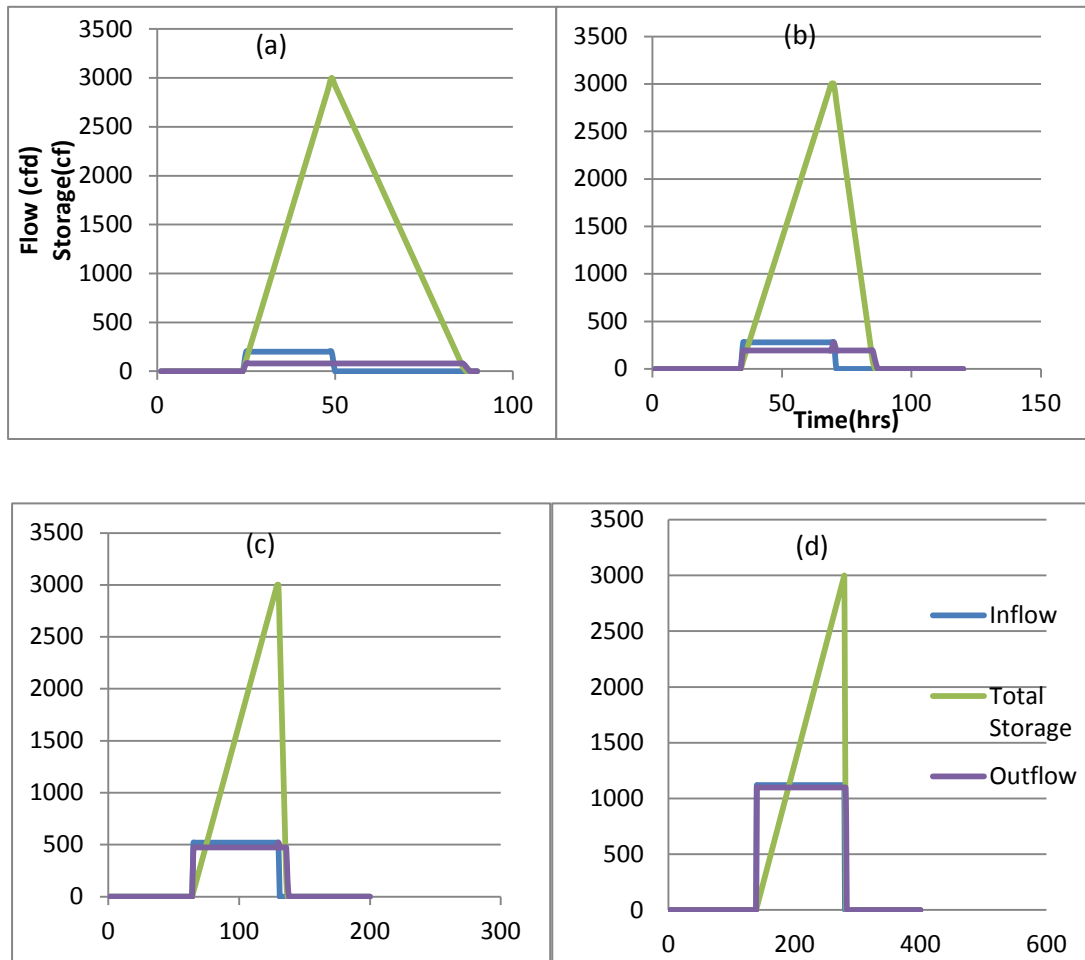


Fig 3.2 Inflow-outflow-storage plot for abrupt hydrograph 2 with Maximum Peak Reduction Rule, inflow hydrograph durations were a) 100 hours, b) 200 hours, c) 400 hours, and d) 1000 hours

Figure 3.3 demonstrates how the reservoir will operate in a rectangular pulse hydrograph and the durations of the storms are determined for visualized purpose.. With a pulse hydrograph, optimal outflow is constant for the whole duration and reservoir storage grows linearly in filing and draw down. Figure 3.3 a shows a significant peak flow reduction in which outflow is almost half of the unregulated inflow. With the increase of the inflow in Figure 3.3 b-d, the reduction becomes less effective. When the inflow is large, Figure 3.3 d, there is very little reduction; the storm is beyond the regulation ability of the reservoir.



**Fig 3.3 Inflow-outflow-storage plot for rectangle hydrograph 3 with Maximum Peak Reduction Rule, inflow hydrograph durations were a) 25 hours, b) 45 hours, c) 90 hours, and d) 150 hours**

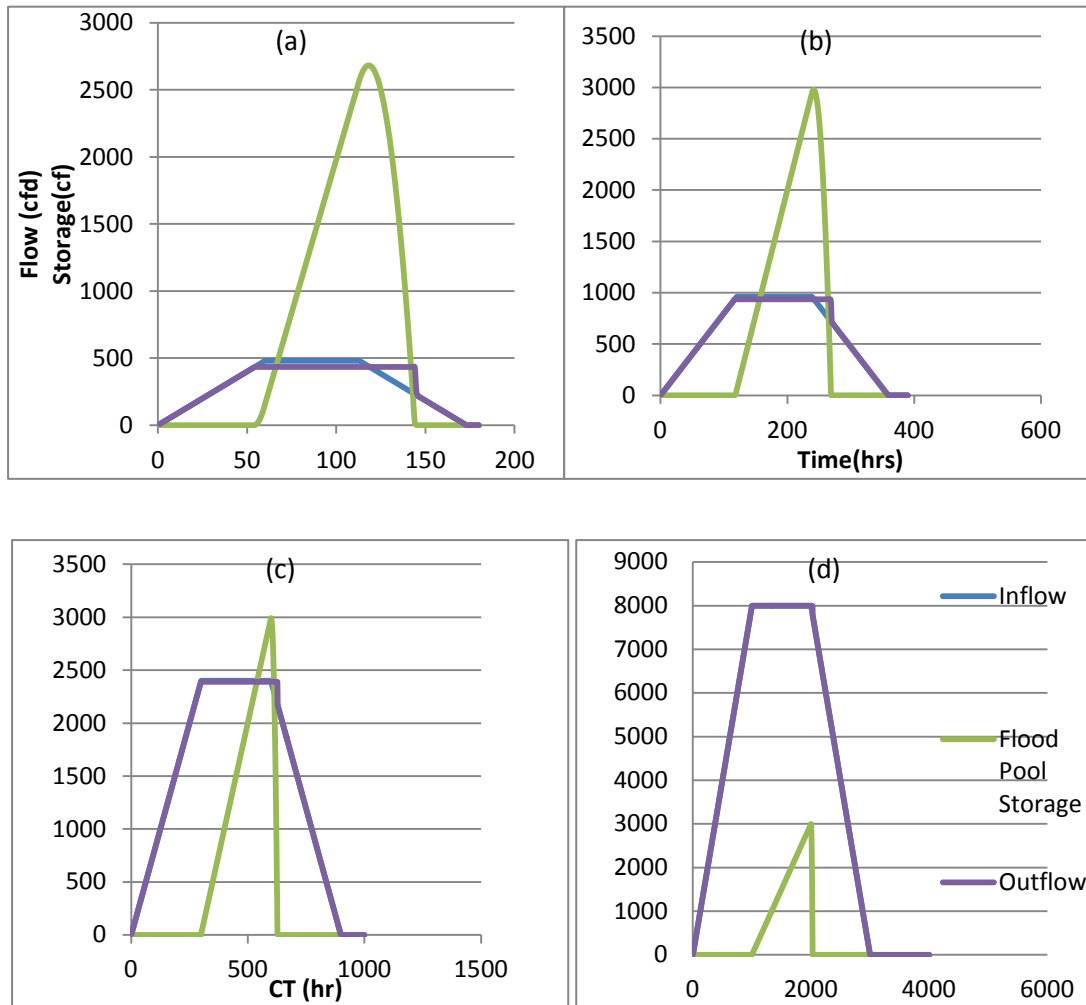


Fig 3.4 Inflow-outflow-storage plot for ladder-shaped hydrograph 4 with Maximum Peak Reduction Rule, peak inflow hydrograph durations were a) 170 hours, b) 340 hours, c) 900 hours, and d) 3000 hours

Broad peak hydrograph is the sum of the triangular hydrograph and the pulse hydrograph, with rising and recession slopes and an extended peak. Similar to earlier figures, the flood pool starts to store flow and outflow remains constant until the inflow reaches the reduction point. After the storing period, outflow equals inflow. Similar to the former three hydrographs, the reservoir has less effective benefits while increasing inflow from Figure 3.4 a-d.

#### 4. Minimize Exceedence of Downstream Channel Capacity Rule

A more common rule for reservoir flood operations is to minimize exceedence of downstream channel capacity. With this rule, when the inflow is less than the downstream channel capacity, outflow equals reservoir inflow, so all inflow is released. The reservoir begins to store the excess flow as inflow exceeds the channel capacity. After the reservoir is fully stored, the outflow again equals to the inflow. On the recession limb of the hydrograph, the reservoir begins to release water at the rate



of the channel capacity once inflow is less than the downstream channel capacity. When the reservoir is empty, outflow again equals inflow.

The Minimize Exceedence of Downstream Channel Capacity Rule differs from the Maximum Peak Reduction Rule. No hydrograph forecast is needed for this rule, only a downstream channel capacity, and the operator wants to minimize flow exceedences of this channel capacity. A downstream channel capacity of 200 CF per day was used for illustrative purposes. The Downstream Channel Capacity Rule assumes the flood control reservoir begins at the top of the conservation pool (bottom of the flood control pool) (FEMA 2003).

Consulting to a similar work done by Ergish (2010), each type of the four different hydrographs was examined over a range of flood volumes. A reservoir with a flood pool capacity of 3,000 CF, a channel capacity of 200 CF and  $r_1=r_2=8$  cfd/hr per day are used for numerical exploration of theory. The large range scale of the flood volumes are for illustrative purpose. Each plot shows the inflow, outflow and the reservoir storage volume.

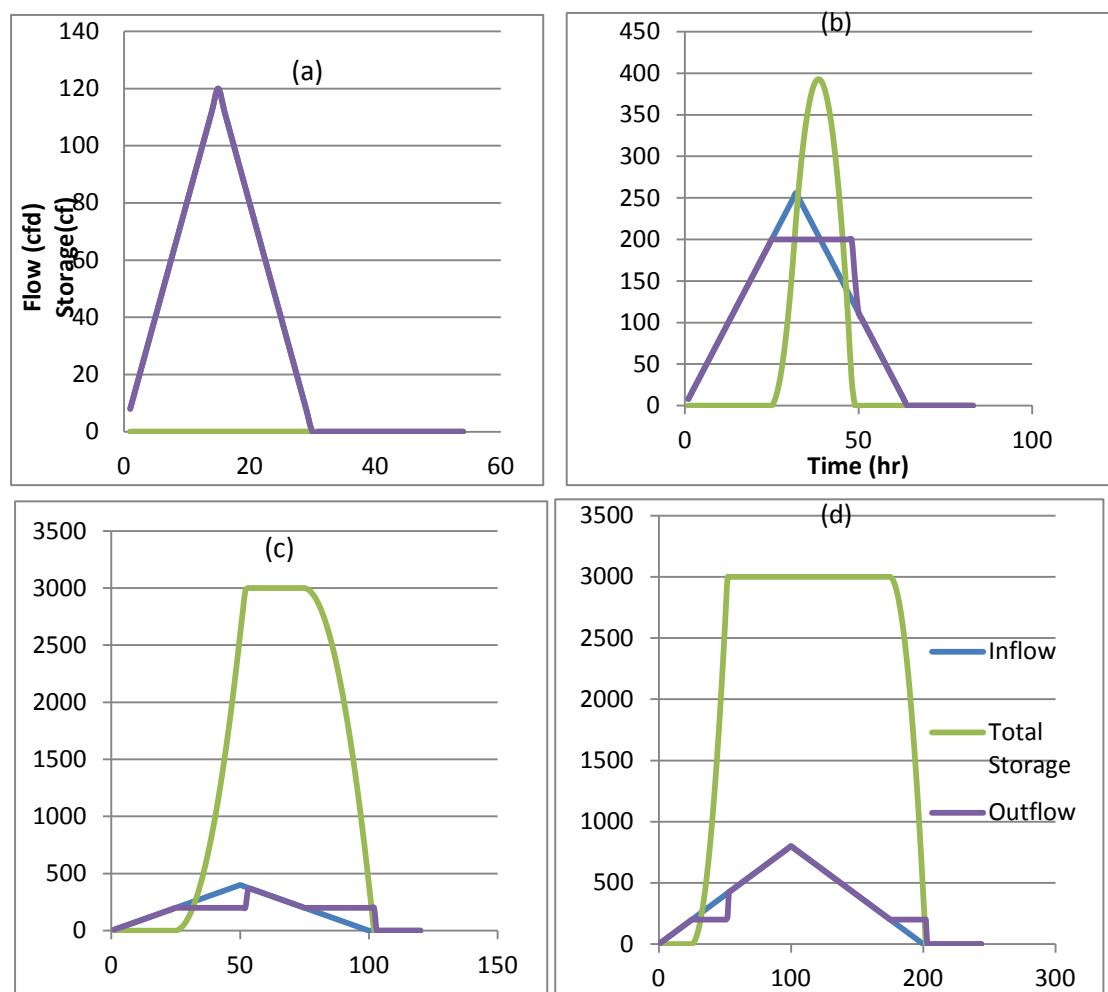


Fig 4.1 Inflow-outflow-storage plot for triangular hydrograph 1 with Minimize Exceedence of Downstream Channel Capacity Rule, inflow hydrograph durations were a) 30 hours, b) 60 hours, c) 100 hours, and d) 200 hours

Figure 4.1 shows how a reservoir reduces the peak of triangular hydrograph 1 with the Minimize Exceedence of Downstream Channel Capacity Rule. Within this rule, the reservoir begins storing excess flow when the inflow exceeds the channel capacity. Figure 4.1.a shows a storm for which inflow never exceeds channel capacity, and outflow always equals inflow. With large volumes, the reservoir begins filling to capture and keep outflow below the downstream channel capacity. In Figure 4.1.b, the outflow line is horizontal when inflow is captured and outflow held the downstream channel capacity. In the later portion of the hydrograph in Figure 4.1.b, when the reservoir is full, outflow again equals inflow after the reservoir empties. In Figure 4.1.c, the horizontal outflow line is shorter, with a step to equal inflow when the reservoir fills. Figure 4.1.d shows the condition that the reservoir fills before the hydrograph's peak flow. There is no reduction in peak outflow, although the channel capacity exceedence is minimized. Ergish (2010) indicated that it may be effective for downstream evacuation.

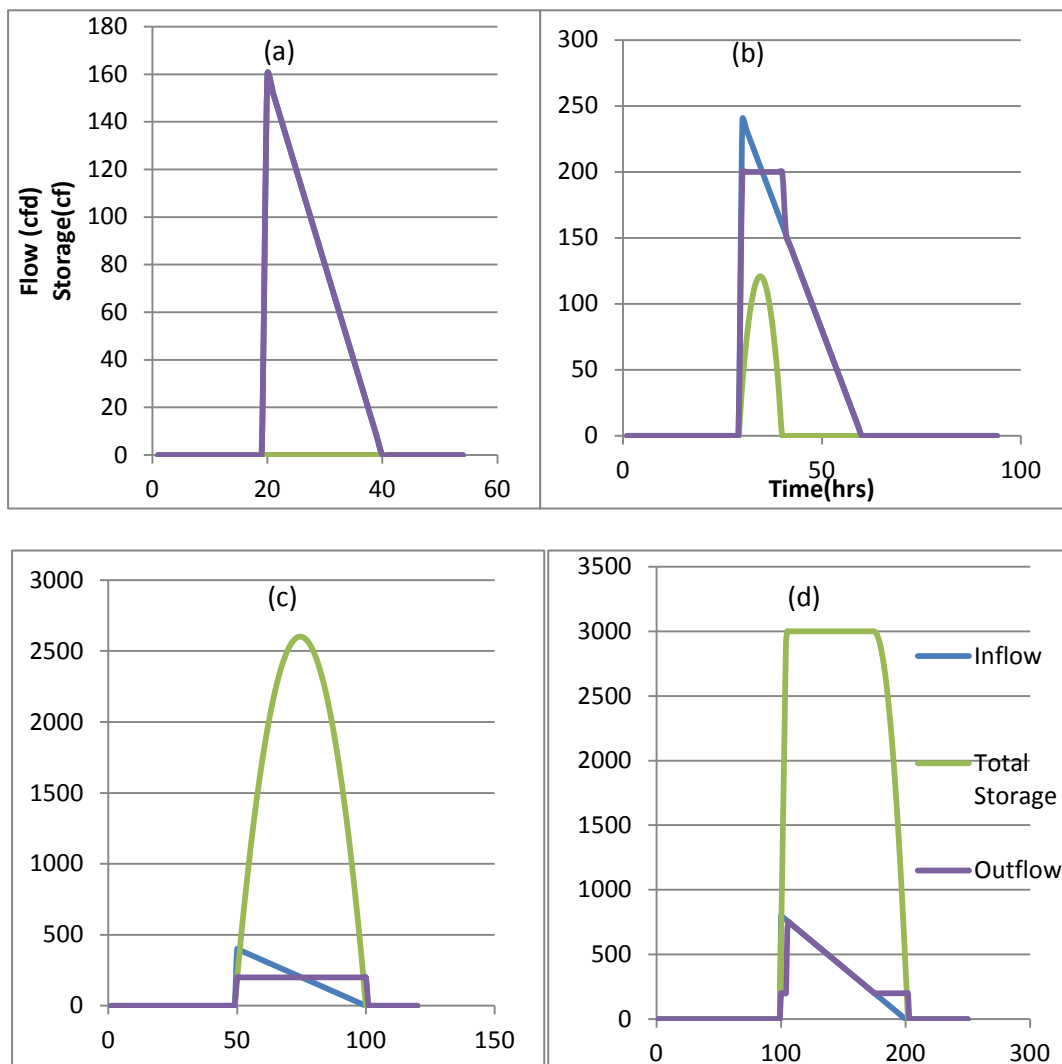


Fig 4.2 Inflow-outflow-storage plot for abrupt hydrograph 2 with Minimize Exceedence of Downstream Channel Capacity Rule, inflow hydrograph durations were a) 20 hours, b) 50 hours, c) 100 hours, and d) 200 hours

The inflow-outflow-storage plots for the abrupt wave hydrograph 2 are similar to hydrograph 1 except that the reservoir starts filling faster as the peak hits abruptly. For such steep hydrographs, the peak flood is usually captured but not always optimally.

Figure 4.2.a shows a storm for which inflow never exceeds channel capacity, so outflow always equals inflow. Similar to the Maximum Peak Flow Reduction Rule, Figure 4.2.b-c shows how the reservoir captures the peak and releases it later in the storm so as not to exceed downstream channel capacity. However, in the condition Figure 4.2.d, when the reservoir storage capacity cannot capture of the entire peak, it begins to release volume more than downstream channel capacity.

Similar to the Maximum Peak Flow Reduction Rule, Minimize Exceedence of Downstream Channel Capacity Rule always produces both a delay and reduction in the outflow peak for an abrupt peak hydrograph. However, the peak reduction is not as optimal as the peak minimizing operations.

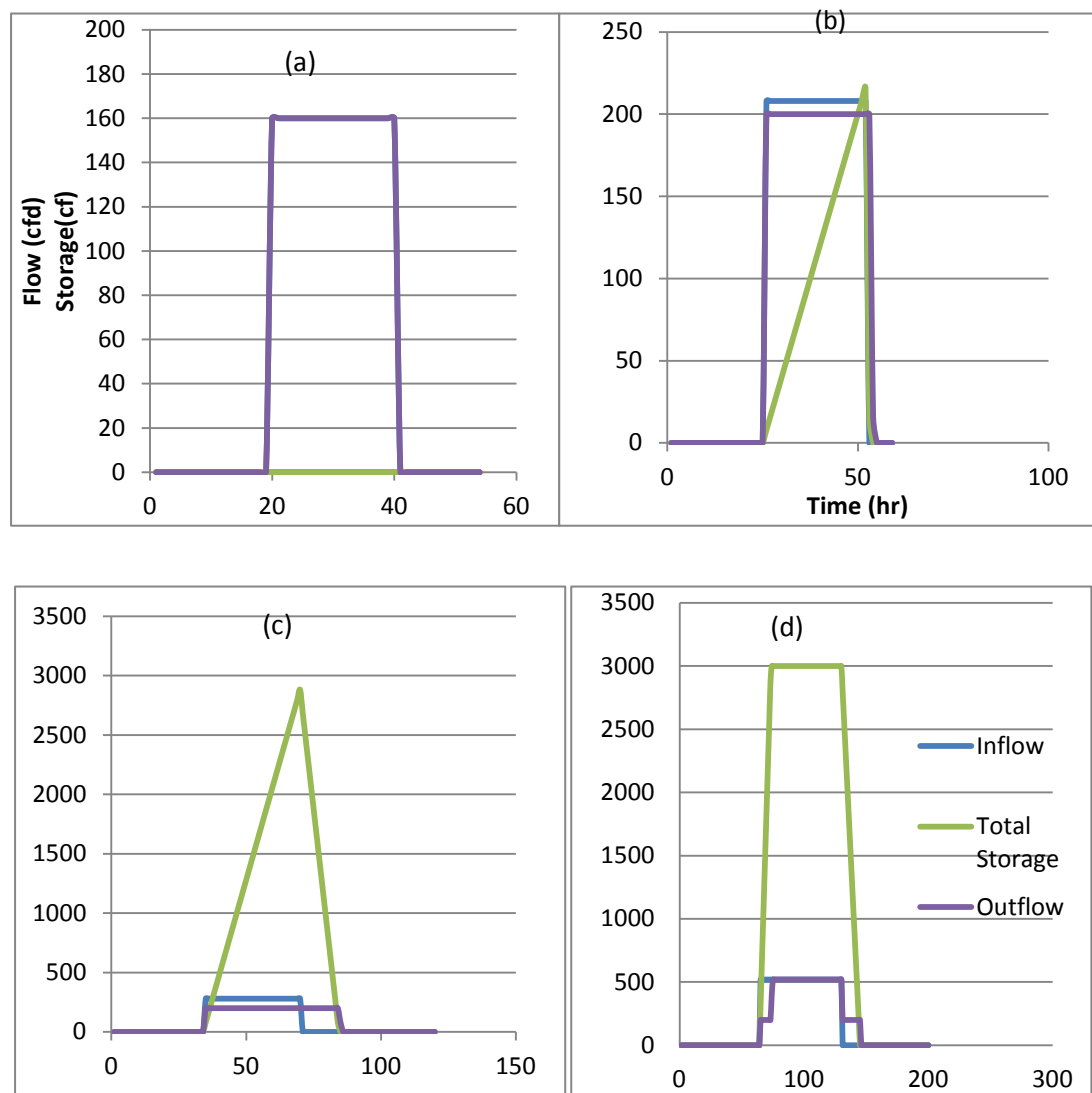
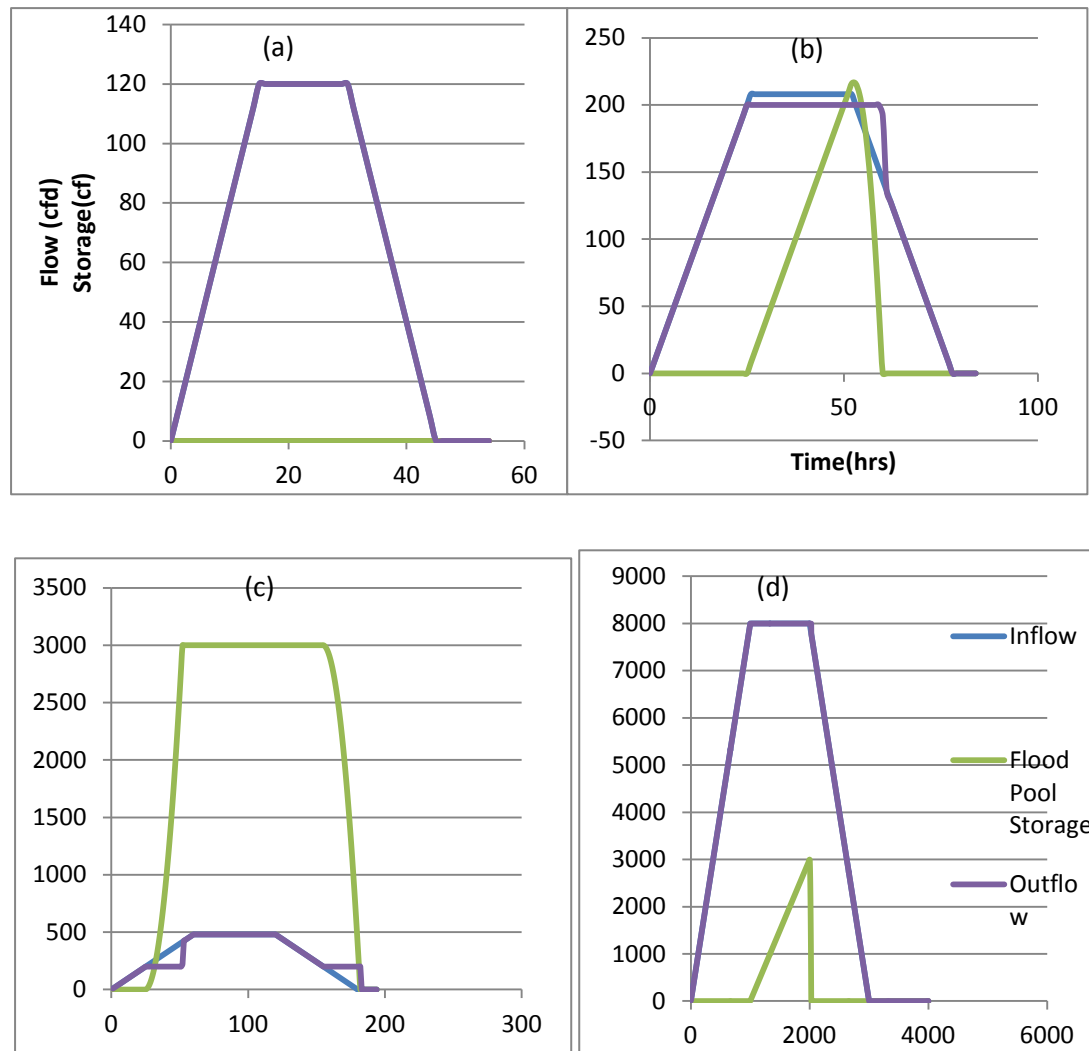


Fig 4.3 Inflow-outflow-storage plot for rectangle hydrograph 3 with Minimize Exceedence of Downstream Channel Capacity Rule, hydrograph durations were a) 20 hours, b) 30 hours, c) 40 hours, and d) 80 hours

The plots of the pulse hydrograph 3 differ from Figure 4.1 and 4.2. Because the hydrograph has a rectangle shape, the peaks are captured in a linear rate and make the rectangle flatter.

Figure 4.3.a shows a hydrograph in which the downstream channel capacity is not exceeded and outflow equals inflow. Figure 4.3.b-c shows how the reservoir captures the peak and releases it later in the storm so as not to exceed downstream channel capacity. Figure 4.3.d illustrates the condition that the reservoir fills in a short time and the hydrograph is too large to capture the entire peak, with the major effect being to briefly delay flooding.

Compared to the Maximum Peak Flow Reduction Rule, under the Minimize Exceedence of Downstream Channel Capacity Rule, operation is less optimal but often effective.



**Fig 4.4 Inflow-outflow-storage plot for ladder-shaped hydrograph 4 with Minimize Exceedence of Downstream Channel Capacity Rule, peak inflow hydrograph durations were a) 45 hours, b) 80 hours, c) 180 hours, and d) 3000 hours**

Figure 4.4 illustrates broad peak hydrograph 4 as it is scaled up to capture a range of storms. Figure 4.4.a shows a hydrograph in which the downstream channel capacity is not exceeded and outflow equals inflow. Figure 4.4.b shows how the reservoir captures the peak and releases it later in the storm so as not to exceed downstream channel capacity. In Figure 4.4.c similar to the triangular hydrograph, the reservoir fills before the hydrograph's peak flow. There is no reduction in peak outflow, although the channel capacity exceedence is minimized. Figure 4.4.d shows the operations when the hydrograph is too large and the operation is minimally effective.

## 5. Maximum Peak Flow Reduction Rule with Incomplete Forecasts

The Maximum Peak Flow Reduction Rule with Incomplete Forecasts add an incomplete forecast to the Maximum Peak Flow Reduction Rule. The rule's objective is also to capture the peak flow.

Assuming that at time 0, if the sum of inflows minus channel capacity from time zero

to forecast time  $\tau$ ,  $\left[ \sum_{t=0}^{\tau} I(t) - Q_c \tau \right]$  exceeds the reservoir storage capacity  $V$ , there

will be channel capacity exceedence in the future. This would tend to be optimal where flood damage is convex with peak flow over the range, so the reservoir might begin releasing this excess water advance to reduce the peak flow.

### 5.1 Derivation

For optimal operations, the best way is to average the future exceedence to the forecast time  $\tau$ , the equation can be written as:

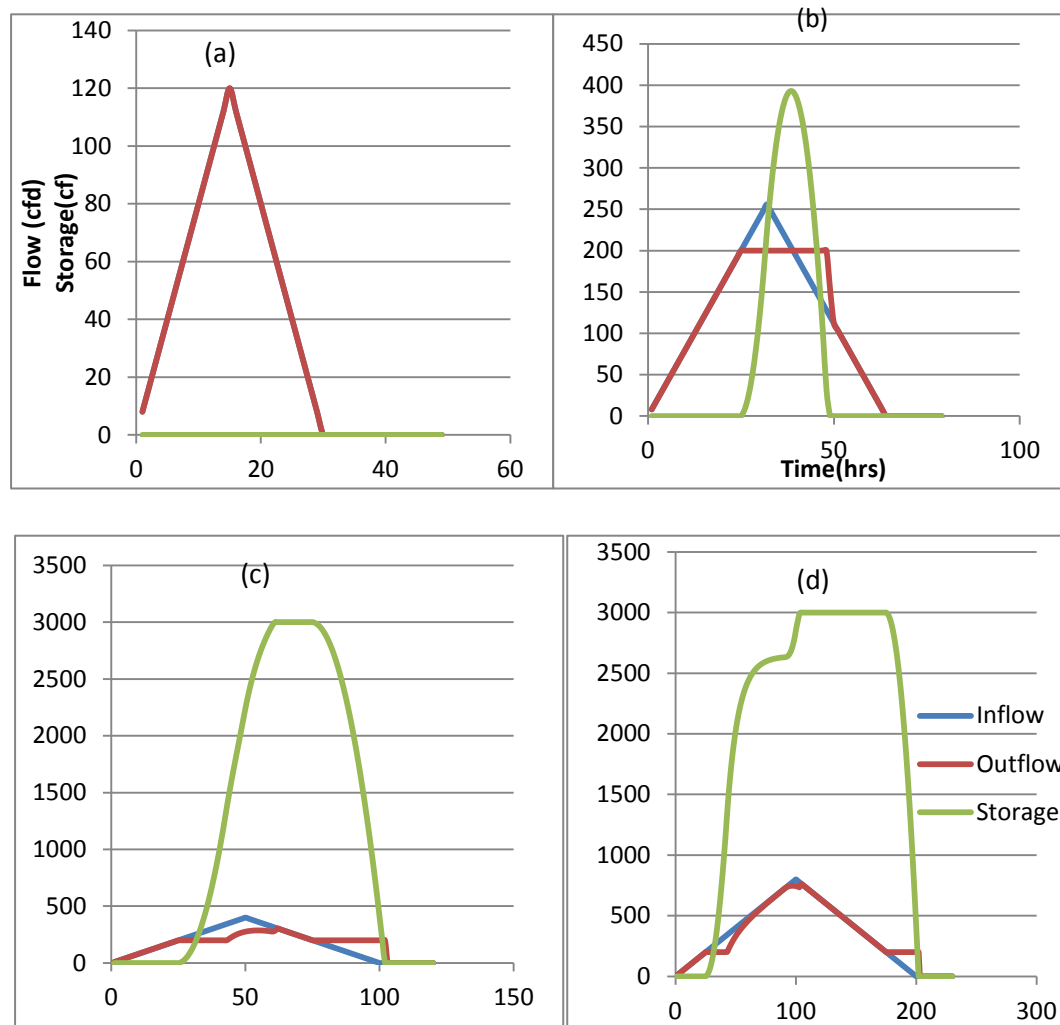
$$\frac{\int_0^{\tau+\tau} S(t) - \int_0^{\tau} S(t) - V - \int_0^{\tau} R(t)}{\tau} = R(t)$$

$S(t)$  is the volume density of the storm at time  $t$ .  $V$  is original reservoir storage capacity.  $R(t)$  is the outflow rate at time  $t$ .

A reservoir with a flood pool capacity of 3,000 CF, a channel capacity of 200 CFD and a forecast time  $\tau = 10$  days were used for numerical exploration. Each time step is one day.

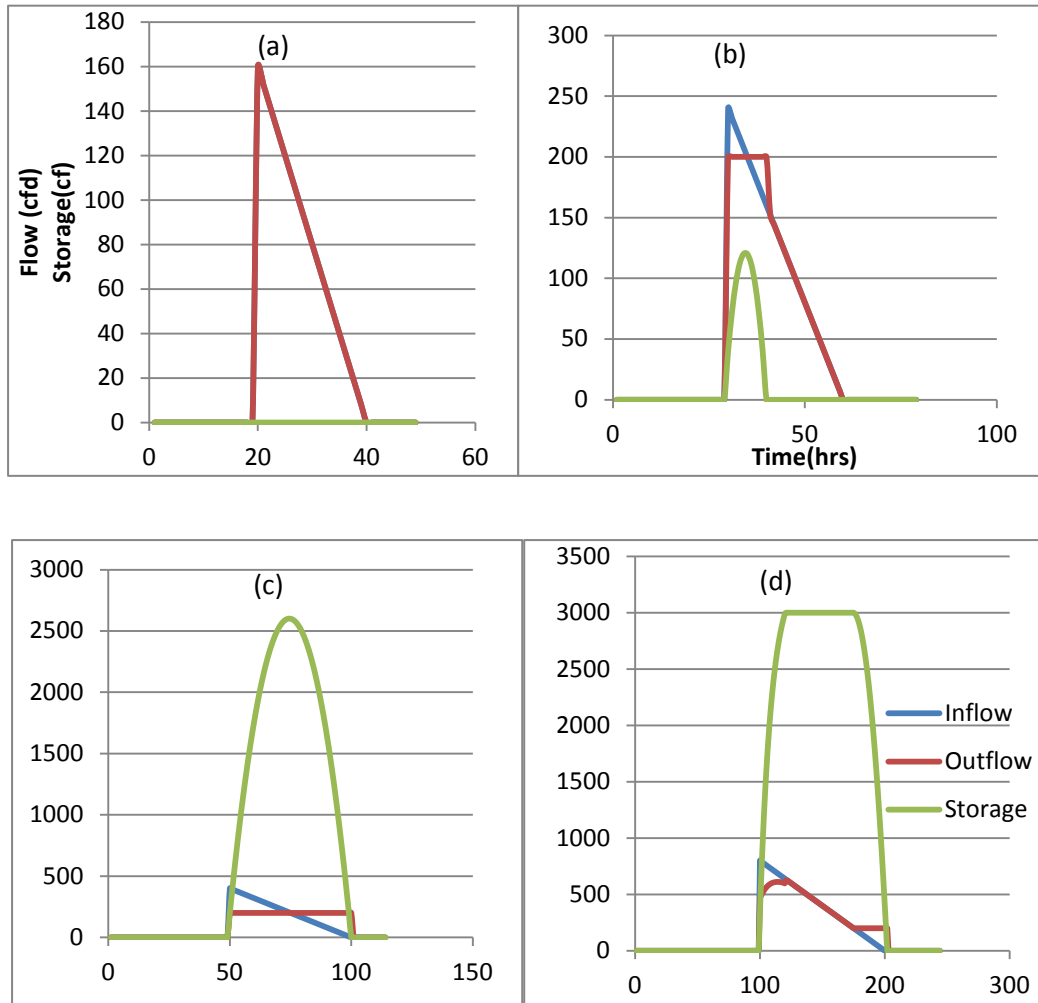
Each of the four different hydrograph types was examined over a range of flood volumes. The range of flood volumes is illustrative. Each plot shows inflow, outflow and reservoir storage volume.

## 5.2 Results



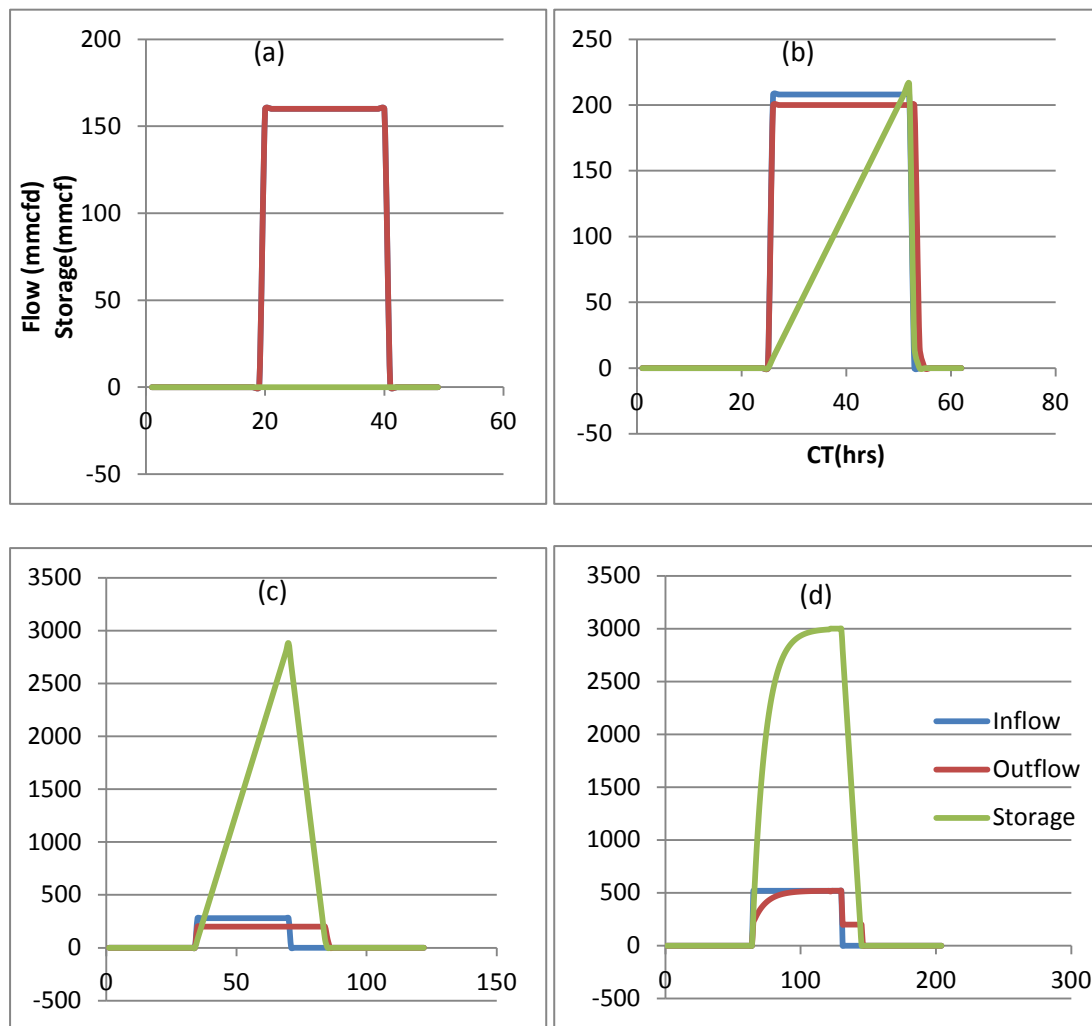
**Fig 5.1 Inflow-outflow-storage plot for triangular hydrograph 1 with Maximum Peak Flow Reduction Rule with an Incomplete Forecast, inflow hydrograph durations were a) 30 hours, b) 60 hours, c) 100 hours, and d) 200 hours**

Figure 5.1 shows how a reservoir would operate in the Maximum Peak Reduction Rule with an incomplete forecast. Compared to Figure 3.1, this operation rule also reduces and delays peak outflow. However, the outflow line is arc-shaped and changes continuously. Figure 5.1 a to d show how the flood pool storage and outflow changes with the increased inflow volume. Figure 5.1.a-b are the same to Figure 3.1.a-b, which means that there's no exceedence in a 10 days forecast, so the operation is the same. In Figure 5.1.c, the reservoir begins to release the future exceedence water at 44 hours, and returns to the channel capacity at 75 hours. In Figure 5.1 d, the flood is too large and the reservoir becomes less effective to capture the peak flow, in which the outflow almost equals inflow. With an incomplete forecast, this rule usually works to capture the peak flow, not ideally, but better than the rule which minimized channel capacity exceedence.



**Fig 5.2 Inflow-outflow-storage plot for abrupt hydrograph 2 with Maximum Peak Flow Reduction Rule with an Incomplete Forecast, inflow hydrograph durations were a) 20 hours, b) 30 hours, c) 50 hours, and d) 100 hours**

The Figure 5.2 is the same to Figure 3.2 except the last plot. For the abrupt shape hydrograph, the Maximum Peak Flow Reduction Rule with complete forecast or with an incomplete forecast will both capture the peak flow. Figure 5.2.a-c shows a storm for which the accumulated net inflow never exceeds the reservoir capacity, so outflow never exceeds the channel capacity. While, in Figure 5.2.d, the accumulated net inflow exceeds the reservoir capacity, so outflow is larger than the channel capacity. The outflow curve is arc-shaped because the accumulated net water inflow changes with time. In each volume of the abrupt hydrograph, this operation rule works well to capture the peak flow.

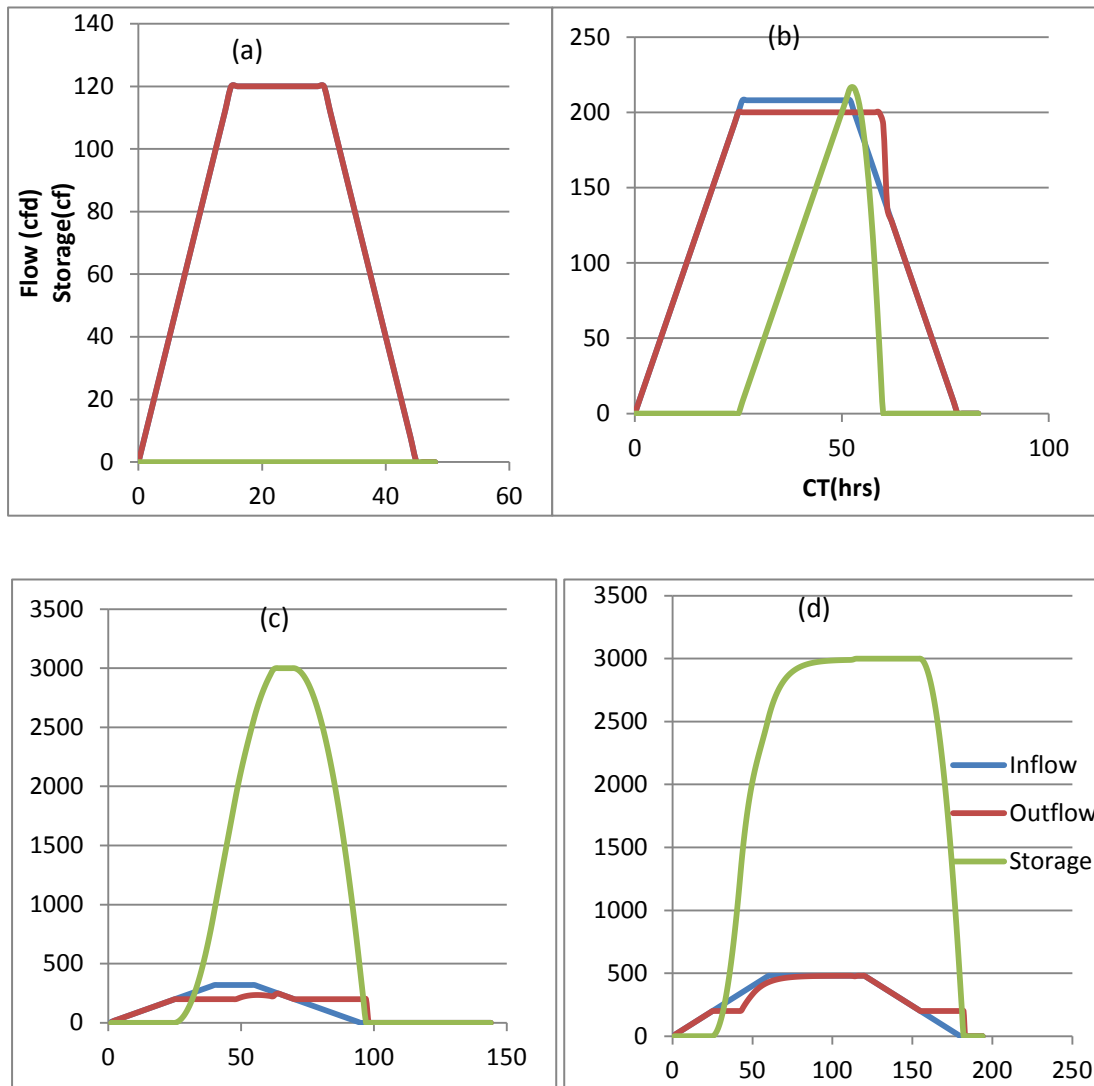


**Fig 5.3 Inflow-outflow-storage plot for rectangle hydrograph 3 with Maximum Peak Flow Reduction Rule with Incomplete Forecast, inflow hydrograph durations were a) 20 hours, b) 30 hours, c) 40 hours, and d) 80 hours**

Figure 5.3.a shows a small hydrograph in which the downstream channel capacity is not exceeded and outflow equals inflow. Figure 5.3.b-c shows how the reservoir captures the peak and releases it later so as not to exceed downstream channel capacity.

Figure 5.3.a-c shows storms for which the accumulated net inflow never exceeds the reservoir capacity, so the outflow never exceeds the channel capacity. However, Figure 5.3.d shows arc-shaped outflow and storage. This differs from the other two operation rules used; the peak in Figure 5.3.d is not captured because the accumulated net inflow changes with time in the forecast period.





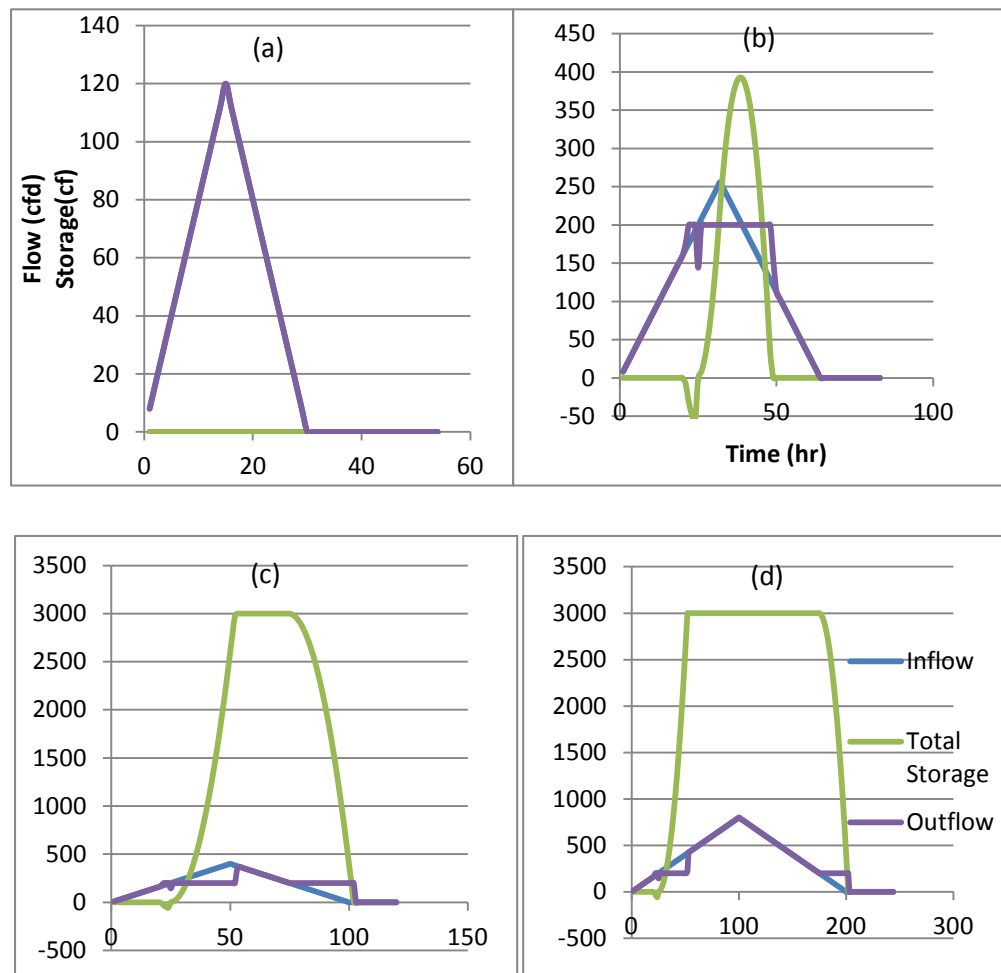
**Fig 5.4 Inflow-outflow-storage plot for ladder-shaped hydrograph 4 with Maximum Peak Flow Reduction Rule with an Incomplete Forecast, inflow hydrograph durations were a) 45 hours, b) 75 hours, c) 100 hours, and d) 180 hours**

Figure 5.4 illustrates broad peak hydrograph 4 as it is scaled up to capture a range of storms. Figure 4.4.a shows a hydrograph in which the downstream channel capacity is not exceeded and outflow equals inflow. Figure 4.4.b shows how the reservoir captures the peak and releases it later so as not to exceed downstream channel capacity. Figure 5.3.a-b shows a storm for which the accumulated net water inflow never exceeds the reservoir capacity, so the outflow never exceeds the channel capacity. In Figure 5.4.c, the accumulated net inflow exceeds the reservoir capacity and the reservoir release exceeds the channel capacity in advance to better reduce the peak flow. Figure 5.4.d shows no reduction in peak outflow, although the channel capacity exceedence is minimized, because the storm is too large to regulate.

## 6. Least Exceedence Probability Rule with Reoperation and Incomplete Forecasts

All operation rules above assume a fixed flood control pool. However, in practice, reoperation can reallocate storage capacity between the flood control pool and conservation pool, by adjusting the elevation of the top of the conservation pool (the bottom of the flood control pool). With an accurate incomplete forecast, the operator can adjust the flood control pool's volume by changing the elevation of the top of the conservation pool. If the forecast accumulation exceeds the flood control pool's volume, the reoperation adjusts the flood control pool's volume and release additional water in advance. The maximum volume of flood control pool adjusting is set as 1,000 CF for illustration.

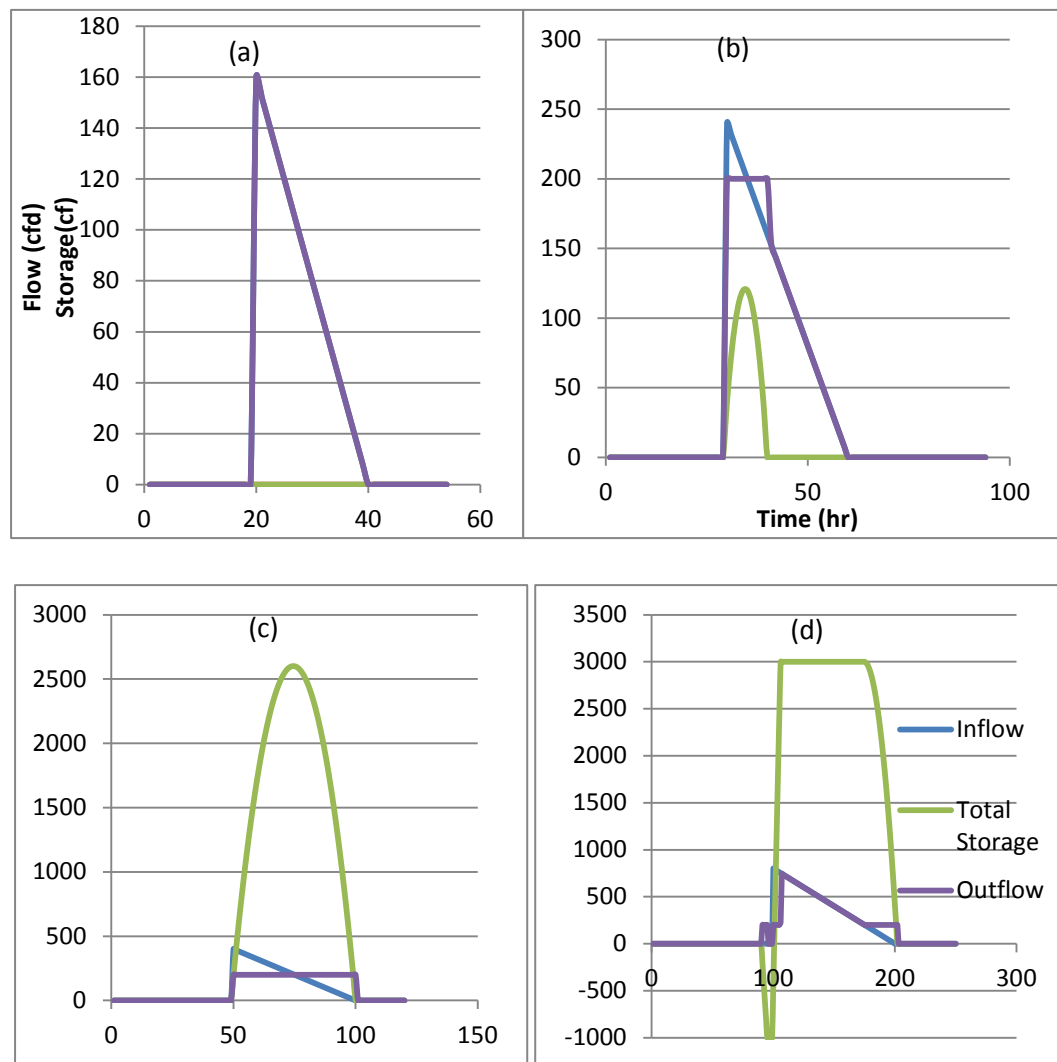
A reservoir with a flood pool capacity of 3,000 CF, a channel capacity of 200 CFD and a forecast time  $\tau = 10$  days were used for illustration. Each time step is one day. The maximum volume of flood control pool adjusting is set as 1,000 CF.



**Fig 6.1 Inflow-outflow-storage plot for triangular hydrograph 1 with Least Exceedence Probability Rule with Reoperation and Incomplete Forecast, inflow hydrograph durations were a) 30 hours, b) 60 hours, c) 100 hours, and d) 200 hours**

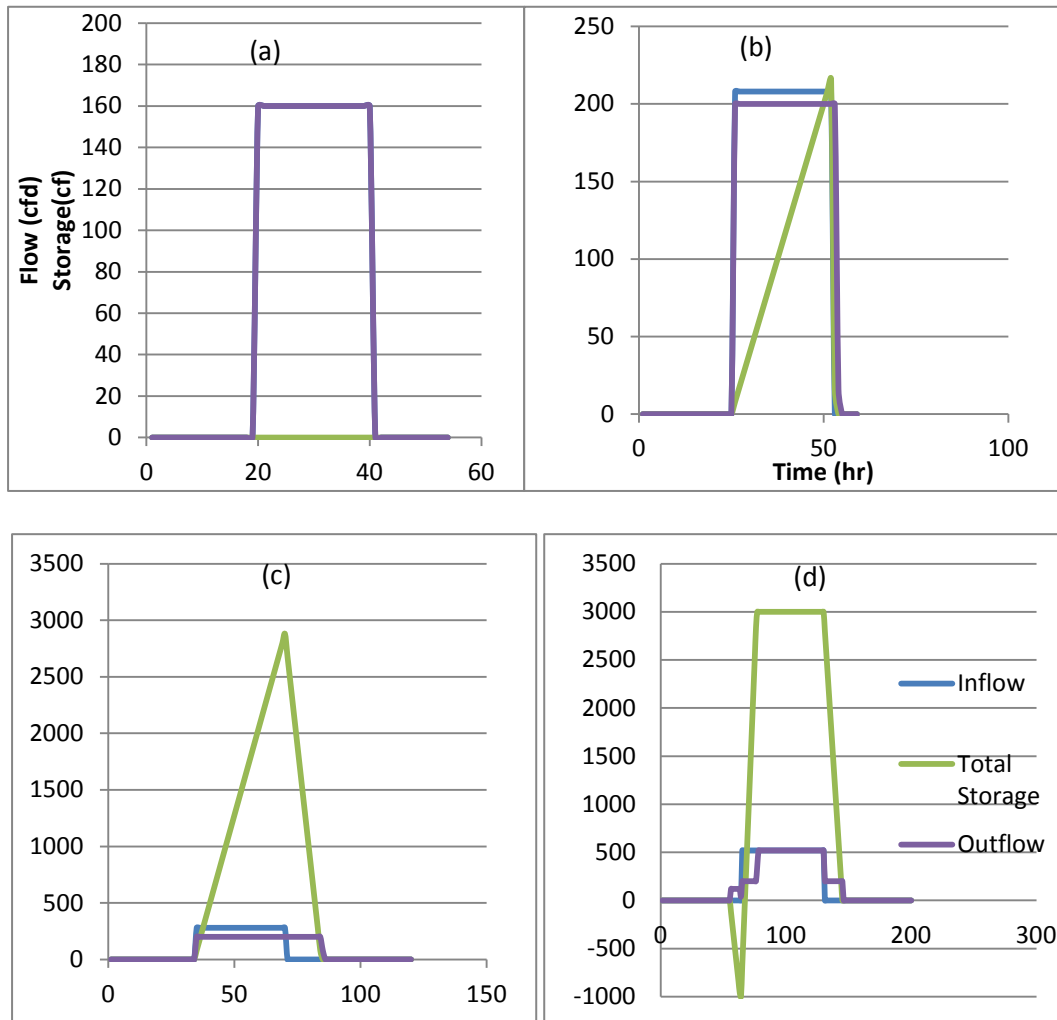
Figure 6.1 shows how a reservoir would operate in the Least Exceedence Probability Rule with Reoperation and Incomplete Forecast. As plotted in the figure, this operation rule cuts and delays the peak outflow.

Figure 6.1.a shows a hydrograph in which the downstream channel capacity is not exceeded and outflow equals inflow. In Figure 6.1.b, there is a significant negative value of the reservoir storage line, which means that the flood control pool is adjusted by lowering the top of the conservation pool. The outflow curve is not continuous because the model is solved by daily time steps. The reservoir releases water in advance to prepare a larger storage volume for the coming peak inflow. Figure 6.1.c shows a similar relationship. In Figure 6.1.d, the flood is too large and the reservoir becomes less effective to capture the peak flow, in which the outflow is almost equals inflow.



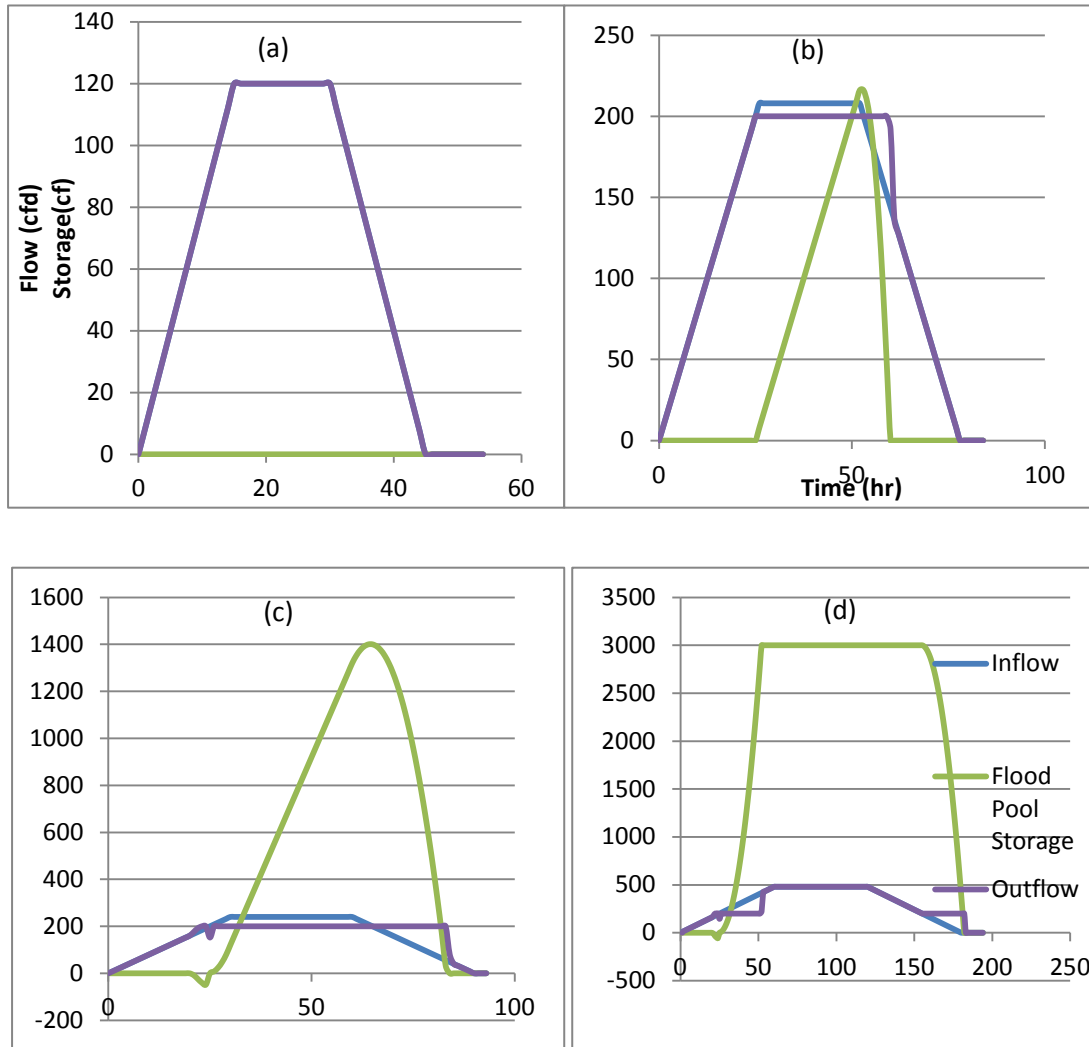
**Fig 6.2 Inflow-outflow-storage plot for abrupt hydrograph 1 with Least Exceedence Probability Rule with Reoperation and Incomplete Forecasts, inflow hydrograph durations were a) 20 hours, b) 30 hours, c) 50 hours, and d) 100 hours**

Figure 6.2.a-c shows a storm for which the accumulated net water inflow never exceeds the reservoir capacity, so the outflow never exceeds the channel capacity and there is no need to release water in advance. In Figure 6.2.d, the accumulated net inflow exceeds the reservoir capacity, so the reservoir begins releasing water before the storm arrives. The reservoir reallocation maximally becomes the -1,000 CF.



**Fig 6.3 Inflow-outflow-storage plot for rectangle hydrograph 1 with Least Exceedence Probability Rule with Reoperation and Incomplete Forecasts, inflow hydrograph durations were a) 20 hours, b) 30 hours, c) 40 hours, and d) 80 hours**

As in Figure 6.2, Figure 6.3.a-c shows a storm for which the accumulated net inflow never exceeds the reservoir capacity, so the outflow never exceeds the channel capacity and there is no need to release water in advance. In Figure 6.2.d, the reservoir also begins releasing water early before the storm and reallocation of storage reaches the maximum value.



**Fig 6.4 Inflow-outflow-storage plot for ladder-shaped hydrograph 1 with Least Exceedence Probability Rule with Reoperation and Incomplete Forecasts, inflow hydrograph durations were a) 45 hours, b) 80 hours, c) 90 hours, and d) 180 hours**

Figure 6.4 also shows the how the reservoir operates under the Exceedence Probability Rule with Reoperation and Incomplete Forecasts. Similar to the triangular shape hydrograph, this operation rule captures the peak flow and releases it later. However, the reoperation is not as effective for both triangular shape hydrograph and trapezoidal hydrographs. Differing from the abrupt and rectangular hydrographs, the rising and recession limbs make the change of the inflow but much more smooth. This restricts the “space” from reallocation.

## 7. Comparison and Conclusion

The four flood operation rule types have their own characteristics. The Maximum Peak Flow Reduction Rule requires a perfect hydrograph forecast and the Minimize Exceedence of Downstream Channel Capacity Rule requires no forecast. The

Maximum Peak Flow Reduction Rule with Incomplete Forecasts and Least Exceedence Probability Rule with Reoperation and Incomplete Forecasts are based on incomplete forecasts.

With the Maximum Peak Flow Reduction Rule with Incomplete Forecasts, assuming that at time 0, if the sum of inflows minus channel capacity from time zero to forecast

time  $\tau$ ,  $\left[ \sum_{t=0}^{\tau} I(t) - Q_c \tau \right]$  exceeds the reservoir storage capacity  $V$ , there will be

channel capacity exceedence in the future. The reservoir begins releasing the “future” excess inflow in advance to reduce the peak flow. As shown in the figures, because the forecast is incomplete and dynamic, the flood damage shows a convex shape over the range. This rule operates optimally in every time step with the dynamic forecast of the storm hydrograph.

With the Least Exceedence Probability Rule with Reoperation and Incomplete Forecasts, a reservoir can reallocate storage capacity between the flood control pool and conservation pool and release additional water in advance if the forecast accumulation exceeds the flood control pool’s volume. With a dynamic forecast and reoperation, this operation rule will achieve a better performance than fixed flood control pool volume operations.

For incomplete forecasts of the hydrograph, both Maximum Peak Flow Reduction Rule with Incomplete Forecasts and Least Exceedence Probability Rule with Reoperation and Incomplete Forecasts work well in the condition of a steep limb or abrupt shaped hydrograph. With this kind of hydrograph, in which the peak flow reaches in a very short time, the incomplete forecast will catch more information about the “real” peak flow. There will be more “space” for optimal operation or reoperation to work. For a flat shaped hydrograph, the “space” for optimal operation or reoperation is very small and the operation result is not effective.

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