Flood Frequency Analysis for Regulated Watersheds

By

NATALIE JEAN ERGISH

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Approved:

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Jay Lund, Chair

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Bassam Younis

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David Ford

Committee in Charge

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Abstract

Flood frequency curves provide the annual probability of exceeding a specific flood flow. Unregulated peak flow frequencies are typically estimated based on a statistical analysis assuming floods are random homogenous events. Bulletin 17B procedures recommend a log-Pearson Type III distribution to fit a curve through observed flood data. However, such statistical analysis is inappropriate for regulated flood flows because they are affected by the flood operation of reservoirs as well as the volumes and peaks of flood hydrographs. A regulated flood frequency curve can be derived from a long unregulated period of flow record based on routing studies and developing a relationship between regulated peak outflow and unregulated inflow peak or volume, often called a peak flow transform. To resolve the interaction of peak flow rate and flood volume, a critical peak duration is often chosen, averaging flow over several days. The unregulated peak flow frequency curve, averaged over a critical duration, is then transformed to produce the regulated peak flow frequency curve. This paper examines the theoretical behavior of regulated peak transforms and provides a short case study within the Feather-Yuba watershed. Two operating 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; and 2) minimized exceedences of downstream channel capacity. The flow transforms developed using these two operating rules seem likely to bound the range of actual peak flow transformations.

Keywords

Flood frequency, flow transform, regulation, reservoirs, simulation models, LOWESS, critical duration

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Chapter 1.0 – Introduction

A flood frequency curve plots the peak annual flow of a particular stream at a specific location against how often that flow is exceeded. Flood frequency curves are developed very differently for unregulated flows and regulated flows, which are affected by reservoir operations, hydraulic structures, operable weirs and diversions, and the effects of levees.

Figure 1 is a simple reservoir schematic that illustrates the location of unregulated and regulated flows within a simple system. The two points of interest, labeled “a” and “b”, are located just upstream and downstream of the reservoir. Point “a” is an unregulated flow location in the system, immediately upstream of the reservoir. Unregulated flows represent the natural flow of the system, unaffected by reservoir storage and operations. In this situation, inflow can be inferred from reservoir storage and release. A statistical analysis can be used because flows are assumed to be random homogenous events. Bulletin 17B recommends a log-Pearson Type III distribution for the analysis of annual series data using a generalized skew coefficient (IACWD 1982). This distribution requires 3 parameters — mean, variance, and skew — which are estimated from the logarithms of the observations rather than the observations themselves. “The Pearson type III distribution is particularly useful for hydrologic investigations because the third parameter, the skew, permits the fitting of non-normal samples to the distribution” (USACE 1993). Incorporating regional estimates in the estimation of the frequency curve can in effect extend longer record lengths and better estimate frequencies for rarer floods (Goldman 2001).

However, Bulletin 17B procedures do not cover watersheds where flood flows are appreciably altered by reservoir regulation because the operated flows are not from a homogenous random sample (IACWD 1982). Flows at point “b” in Figure 1, just downstream of the reservoir outlet, are regulated by reservoir storage and operations upstream. The shape of the regulated flood frequency curve varies with at-site storage characteristics of the reservoir, the frequency of inflow peak, volumes, and storm durations, and the reservoir’s operating policies. The regional information used to increase record lengths statistically is only useful for determining the reservoir inflow frequency curve. The duration of flood volumes critical to determining peak annual outflow, operational contingencies, and the relationship between regulated and unregulated flow values must be considered when converting the inflow frequency curve to a regulated frequency curve (Goldman 2001).

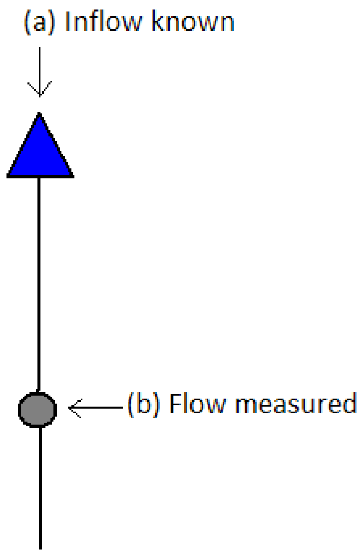

Figure 1. Simple schematic of unregulated - regulated flows

While the literature on flood frequency is extensive, theory for the peak flow transform is scarce. This paper focuses on the theory of peak flow transforms for two simple reservoir operating rules with a variety of hydrograph shapes. The first rule is ideal minimization of peak outflow rate, which requires a perfect flood hydrograph forecast. The second rule minimizes the volume of downstream channel capacity exceedence during flood operations, without a hydrograph forecast. An exploration is also made of inflow averaging periods effects on peak outflow versus inflow relationships for the Feather-Yuba system.

Chapter 2.0 – Development of the Regulated Flow Frequency Curve

The basic steps for developing a regulated frequency curve include developing an unregulated period of flow record based on routing studies, estimating unregulated volume-duration frequency curves, determining the critical duration for flood inflows to the reservoir, and developing a regulated peak outflow and unregulated inflow volume relationship. Combining the critical unregulated volume-duration frequency curve with the unregulated-regulated relationship will produce the regulated frequency curve (Goldman 2001). Figure 2 illustrates this approach for obtaining a regulated outflow frequency curve using the following steps:

1. Develop an unregulated flow time series by routing the unregulated reservoir inflows through a system model. Unregulated flows correspond to the absence of reservoir storage. If the system is regulated, the record would need to be adjusted to remove the effects of regulation before routing through the unregulated model.
2. Using statistical procedures, such as those in Bulletin 17B, develop an unregulated frequency curve using the unregulated flow time series.
3. To assess the effect of regulation on the system, route the unregulated flow time series through a regulated system model.
4. Develop a relationship of unregulated peak flows and their corresponding regulated peak flows using the unregulated and regulated time series. This transforms the unregulated peak flow-frequency curve to a regulated peak flow-frequency curve.
5. Using the unregulated peak flow frequency curve, an unregulated peak flow (or volume) is established for a specified probability (Figure 2a).
6. This unregulated peak flow (or volume) is then used to obtain the corresponding regulated peak flow using the peak flow transform curve (Figure 2b).
7. The specified probability used in step 1 and the regulated peak flow from step 2 define one point on the regulated frequency curve (Figure 2c).
8. This process is continued for a range of probabilities to define the regulated peak flow frequency curve.

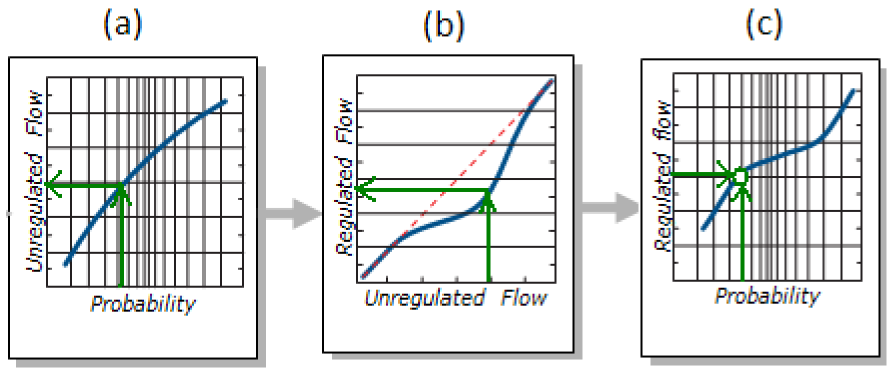

Figure 2. Overview of steps for developing the regulated peak outflow frequency curve (adapted from USACE 2008)

2.1 – Critical Duration for Flood Inflows to the Reservoir

Reservoir regulation reduces the peak storm by storing the highest inflows for release later. To account for this in the development of the regulated frequency curve, the unregulated-regulated peak flow relationship does not compare the day-to-day averages but rather the annual critical peak durations (e.g., 1-day, 3-day, 7-day). The annual critical peak duration of the inflow hydrograph greatly affects the outflow peak. Without regulation, the regulated peak equals the unregulated peak, and the critical duration is irrelevant. As upstream storage increases, the critical duration lengthens because reservoir storage attenuates the inflow peaks and causes the inflow volume to have more effect on the downstream peak flow (USACE 2009).

The critical duration for inflows to a reservoir depends upon the reservoir's storage capacity, its outlet capacity, operating rules, and the uncontrolled area between the dam and downstream locations of interest. The frequency of instantaneous peak inflows to reservoirs is rarely critical to determining the frequency of regulated outflows. Inflow volumes and durations are usually more important.

2.2 – Period of Record Adjustments and Scaling

In many instances, the period of record lacks floods large enough to estimate the regulated frequency curve for the most important, rare, and large floods. Rare events (e.g., p=0.002) are the most critical in defining the upper end of the unregulated-regulated relationship and in better estimating the relationship between unregulated and regulated flows. Engineer Manual (EM) 1110-2-1415 suggests "it is usually possible to use one or more large hypothetical floods (whose frequency can be estimated from the frequency curve of unregulated flows) to establish the corresponding magnitude of regulated flows. These floods can be multiples of the largest observed floods or of floods computed from rainfall; but it is best not to multiply any one flood by a factor greater than two or three" (USACE 1993). If the period of record is regulated, the effects of regulation need to be removed and the flows rerouted to establish the unregulated frequency curve.

2.3 – Initial Reservoir Elevation Assumptions

The assumption is made either that the initial reservoir elevation is at the bottom of the flood control pool or higher because of some special knowledge about the relationship between antecedent storms and major floods. Goldman (2001) suggests that the "simplest and most defensible approach is to assume the initial water surface elevation is at the bottom of the flood control pool and use a historical or design event of sufficient or critical duration that brings the reservoir elevation to an appropriate level prior to the peak inflow".

For this paper, the assumption is made that the initial reservoir elevation is at the bottom of the flood control pool. This provides maximum available storage in the reservoir for peak flow reduction and minimizing the volume of downstream channel capacity exceedence.

This paper first examines the theoretical basis of behavior of the transform from unregulated to regulated peak flows. This is followed by a case study focusing on the development of a regulated frequency curve on the Feather River below the confluence with the Yuba River following the procedures discussed previously. For purposes of the theoretical section of this paper, unregulated flows are the inflows to the reservoir and regulated flows are the outflows from the reservoir only.

Chapter 3.0 – Theoretical Derivation of Peak Inflow-Outflow Relationships

The unregulated-regulated curve needs to reflect the relationship between the inflow flood volume and the peak regulated flow. Factors to consider in obtaining this relationship are: 1) reservoir operating rules and constraints; 2) inflow hydrograph shape and volume; and 3) reservoir flood storage capacity. To explore the theoretical basis for the shape of this curve, four simplified inflow hydrograph shapes were analyzed for two rules: 1) maximum peak reduction with perfect foreknowledge of the flood hydrograph; and 2) minimized exceedences of downstream channel capacity; requiring no hydrograph foreknowledge.

3.1 – Simple Inflow Hydrographs

The four basic hydrographs used in this theoretical analysis appear in Figure 3. Each inflow hydrograph will be analyzed to determine the peak outflow based on the peak inflow ($Q_{p,in}$), storage volume (V), rising and recession limbs (r), and duration of the peak (d). Hydrograph 1 has a simple triangular shape with linear rise and recession. Hydrograph 2 has an abrupt flood wave followed by a linear recession. Hydrograph 3 is a simple rectangular pulse. And Hydrograph 4 is trapezoidal with an extended peak between the rising and recession limbs. These hydrographs are scaled to produce small and large storm events to create the transform. These show how the transform of unregulated to regulated peak flows varies with hydrograph shape and volume. These transforms are developed for the two flood operation rules.

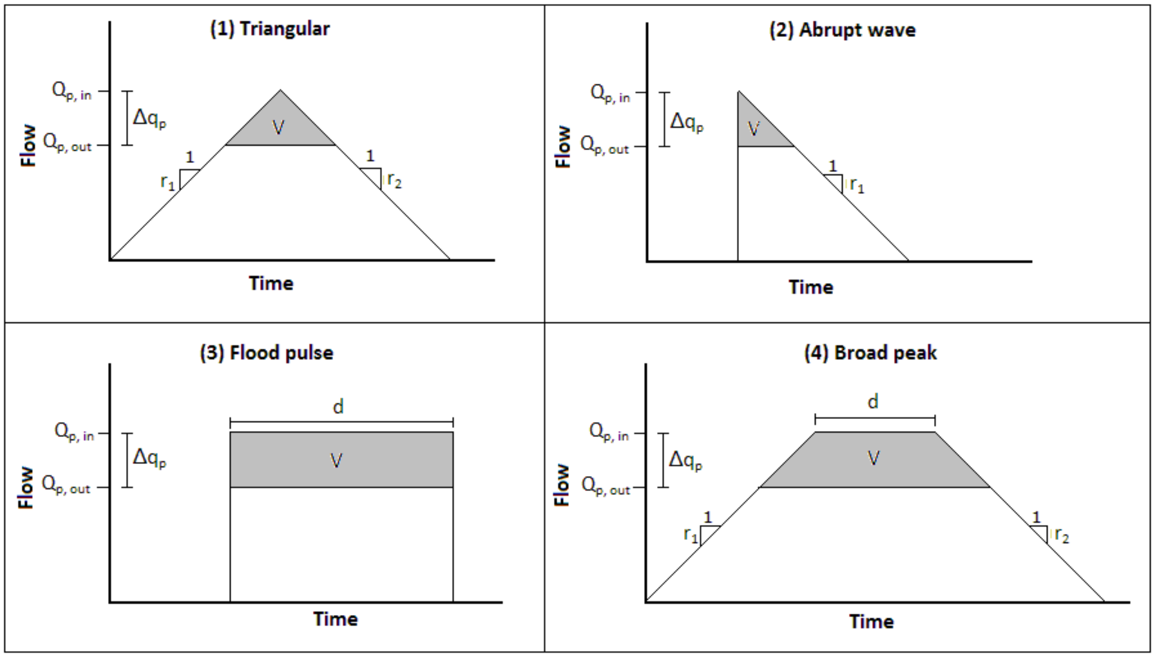

Figure 3. Four basic hydrographs

3.2 – Maximum Peak Flow Reduction Rule

3.2.1 – Derivation

A maximum peak reduction rule ideally requires a perfect flood hydrograph forecast to determine optimal reservoir operation. The inflow hydrograph is analyzed for the greatest peak reduction with perfect knowledge of the peak inflow, storage volume, rising and recession limbs, and length of the peak. The only restraint on the system is the size of the reservoir.

Equations for the peak outflow can be derived based solely on characteristics of the four inflow hydrographs discussed above:

Triangular, Hydrograph 1:

$$\Delta q_p = Q_{p,in} - Q_{p,out} \tag{1}$$

$$V = \frac{\Delta q_p{}^2}{2r_1} + \frac{\Delta q_p{}^2}{2r_{21}} \tag{2}$$

$$\Delta q_p = \sqrt{\frac{2Vr_1r_2}{r_1 + r_2}} \tag{3}$$

$$Q_{p,out} = Q_{p,in} - \sqrt{\frac{2Vr_1r_2}{r_1 + r}} \tag{4}$$

Abrupt wave, Hydrograph 2:

$$\Delta q_p = Q_{p,in} - Q_{p,out} \tag{5}$$

$$V = \frac{\Delta q_p{}^2}{2r} \tag{6}$$

$$\Delta q_p = \sqrt{2Vr} \tag{7}$$

$$Q_{p,out} = Q_{p,in} - \sqrt{2Vr} \tag{8}$$

Flood pulse, Hydrograph 3:

$$\Delta q_p = Q_{p,in} - Q_{p,out} \tag{9}$$

$$V = d\Delta q_p \tag{10}$$

$$\Delta q_p = \frac{V}{d} \tag{11}$$

$$Q_{p,out} = Q_{p,in} - \frac{V}{d} \tag{12}$$

Broad peak, Hydrograph 4:

$$\Delta q_p = Q_{p,in} - Q_{p,out} \tag{13}$$

$$V = \Delta q_p d + \frac{1}{2}\Delta {q_p}^2 r_1 + \frac{1}{2}\Delta {q_p}^2 r_2 \qquad (14)$$

$$\Delta q_p = \frac{-d \pm \sqrt{d^2 - 2(r_1 + r_2)(-V)}}{(r_1 + r_2)} \qquad (15)$$

$$Q_{p,out} = Q_{p,in} - \frac{-d \pm \sqrt{d^2 - 2(r_1 + r_2)(-V)}}{(r_1 + r_2)} \qquad (16)$$

Since,

$$V = \Delta q_p d + \left(\frac{r_1 + r_2}{2 r_1 r_2}\right)\Delta {q_p}^2 \qquad (17)$$

if the rising and falling slopes of the hydrograph are very steep, approximating a pulse flow, the last term becomes negligible and $\Delta q_p = V/d$. For the more general case, this equation is solved by a quadratic formula.

The outflow equals $Q_{p,out}$ if Q_{in} exceeds the calculated $Q_{p,out}$ from the equations above. If Q_{in} is less than $Q_{p,out}$, the outflow equals $Q_{p,out}$ or Q_{in} and the storage within the reservoir, whichever is smaller. Storage in the reservoir is simply the remainder of inflow not released as outflow.

3.2.2 – Inflow-Outflow-Storage Plots

Each of the four hydrographs was examined over a range of flood volumes. Figure 4 to Figure 7 illustrate the inflow, outflow, and reservoir storage for each hydrograph. For this theoretical derivation, a reservoir with a storage capacity of 2,788 cubic feet was used and the four hydrographs were scaled by a large range of ratios for illustrative purposes only.

Figure 4 shows how a reservoir would operate to minimize the peak for a triangular hydrograph. Figure 4a-d show how the reservoir storage use changes as the triangular hydrograph increases in peak and volume, keeping the same rising and falling slopes. Figure 4a-c illustrates peak-minimizing operation in which inflow equals the outflow until the peak can be optimally reduced, at which time the reservoir begins to store the peak. With a known storm hydrograph, the reservoir can directly and optimally capture the peak. Figure 4d shows a case where the storm is too large to capture the entire peak of the hydrograph and outflow equals inflow for almost all of the hydrograph. For this triangular hydrograph, additional storage becomes less effective at reducing peak outflow for larger hydrographs, since more of the widening base of the hydrograph must be stored to reduce the peak outflow by an additional unit of flow.

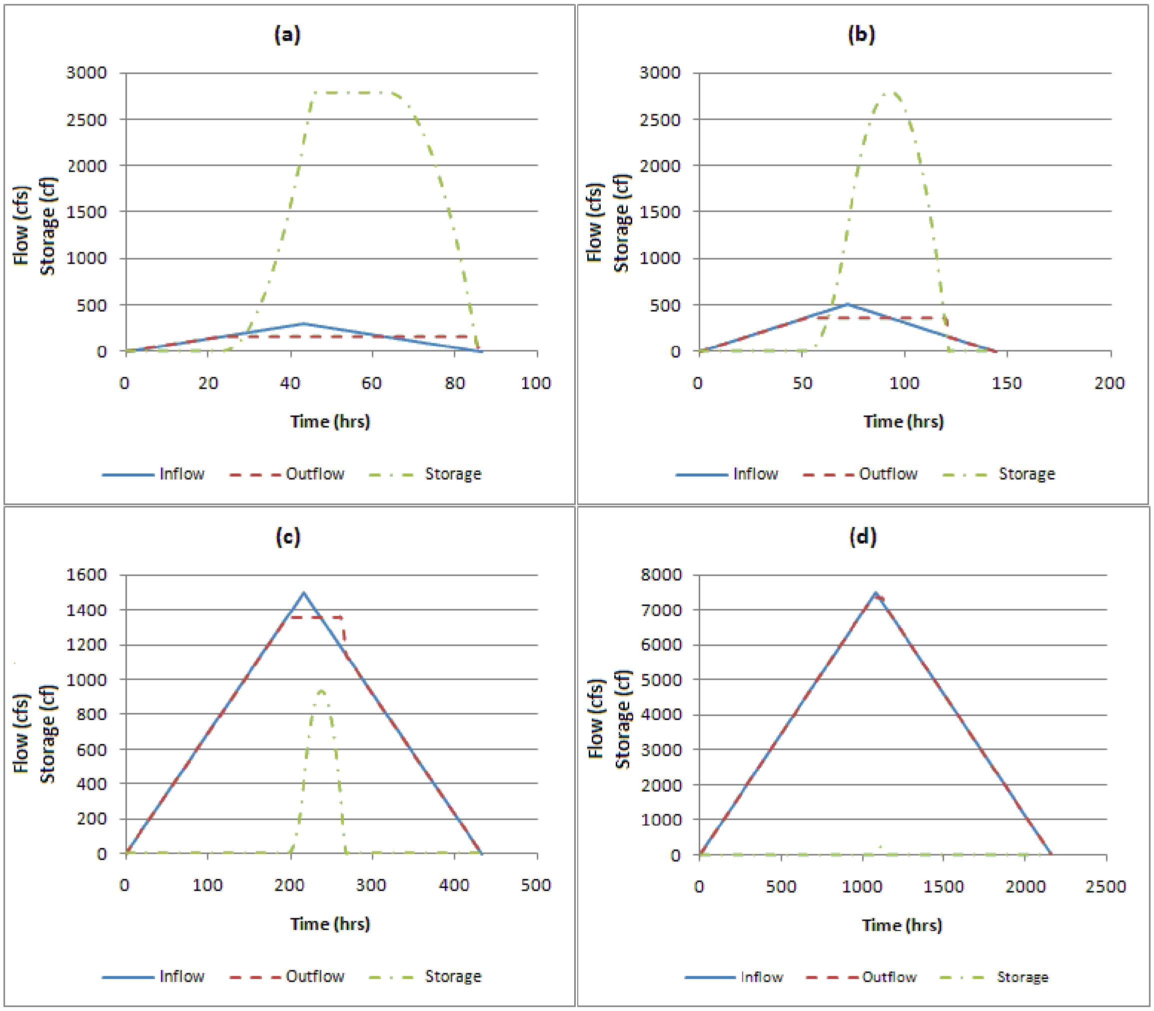

Figure 4. Inflow-outflow-storage plots for triangular hydrograph 1 with Maximum Peak Reduction Rule; Δq_p*=139 cfs*

Figure 5 demonstrates how a reservoir will behave for the abrupt wave hydrograph 2. The sudden increase in flow causes the reservoir to begin storing water sooner than for the more slowly rising hydrograph 1. Figure 5 is similar to Figure 4 in that outflow will equal inflow until the peak can be optimally reduced, at which time the reservoir stores the peak of the storm, if possible. As the scale of the storm increases, reservoir capacity is filled quickly but effectively, after which outflow equals inflow. With these perfect operations, capacity is always filled, except for trivial storms, but never exceeded. Figure 5d shows the situation where the immense size of the storm only allows the reservoir to capture a small part of the peak before exceeding capacity and the outflow must equal the inflow.

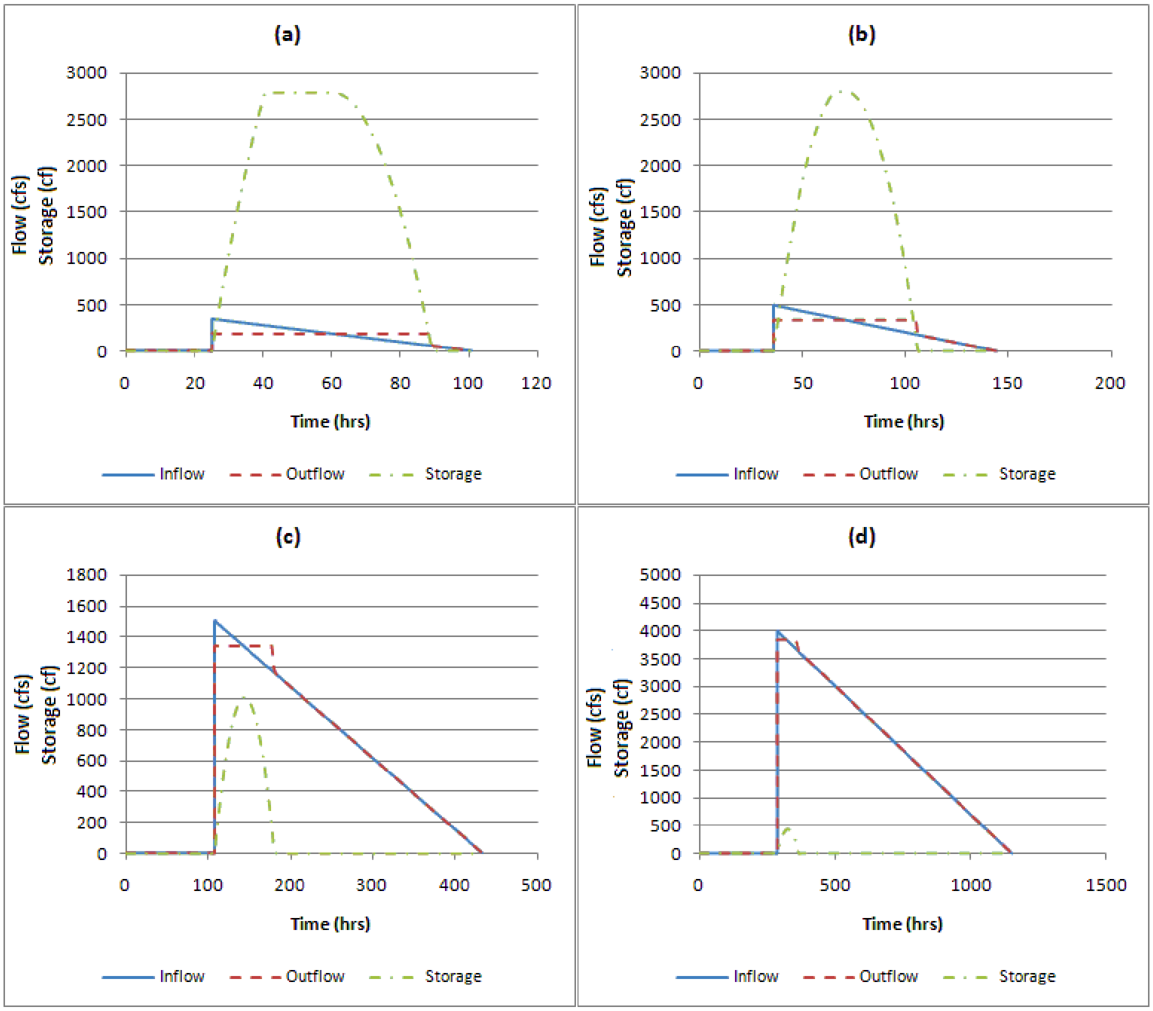

Figure 5. Inflow-outflow-storage plots for abrupt wave hydrograph 2 with Maximum Peak Reduction Rule; Δq_p*=161 cfs*

The flood pulse hydrograph 3 differs from hydrographs 1 and 2 in having an extended peak flow. This affects the inflow, outflow, and storage in Figure 6. The reservoir begins filling at a linear rate at the peak of the storm until it reaches its maximum capacity. With these perfect operations, outflow equals inflow until the peak of the storm can be optimally reduced by the use of reservoir storage. Figure 6a illustrates a smaller, more frequent storm in which most of the peak can be stored within the reservoir, and the outflow is less than the inflow. As the storm increases in Figure 6b-c, the reservoir capacity is exceeded more quickly and the reservoir outflow must equal the reservoir inflow. Figure 6d shows the case when only a small portion of the peak is reduced due to the immense size of the storm and the capacity of the reservoir. For this case, the outflow equals the inflow for most of the storm duration.

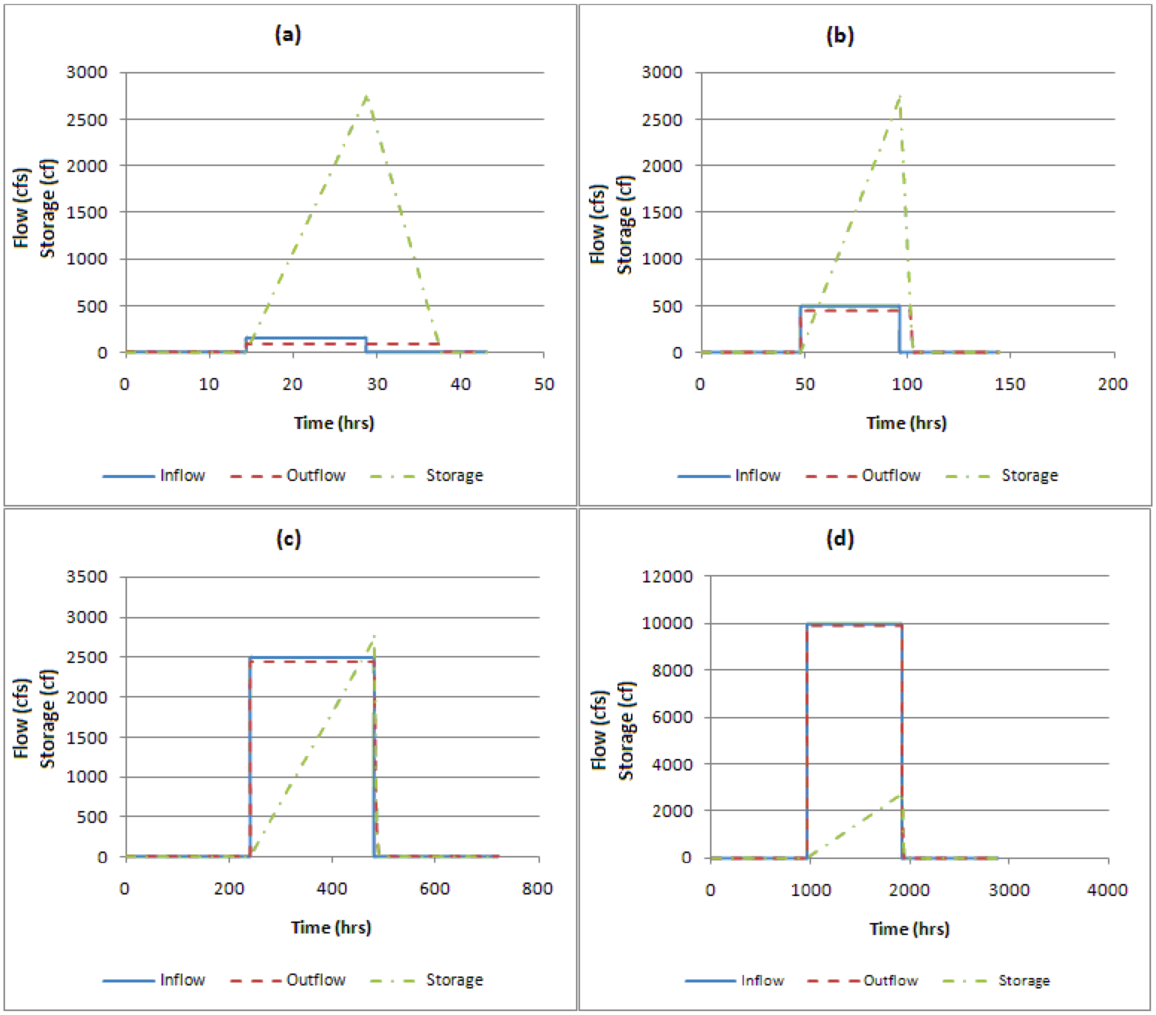

Figure 6. Inflow-outflow-storage plots for flood pulse hydrograph 3 with Maximum Peak Reduction Rule; $\Delta q_p = 57$ *cfs*

The broad peak hydrograph 4 is similar to the flood pulse hydrograph 3 with the extended peak, with the addition of more gradually sloped rising and recession limbs. This slightly changes the inflow-outflow-storage plots in Figure 7, but the concept is similar. Figure 7a illustrates a smaller storm for which the entire peak can be captured and stored in the reservoir. Outflow only equals inflow until the peak can be optimally stored and again after the peak has been reduced. As the storm increases, shown in Figure 7b-d, the reservoir has less capacity to reduce the peak for this broader hydrograph. The large storm in Figure 7d allows very little of the peak to be stored in the reservoir and outflow equals inflow for most of the storm.

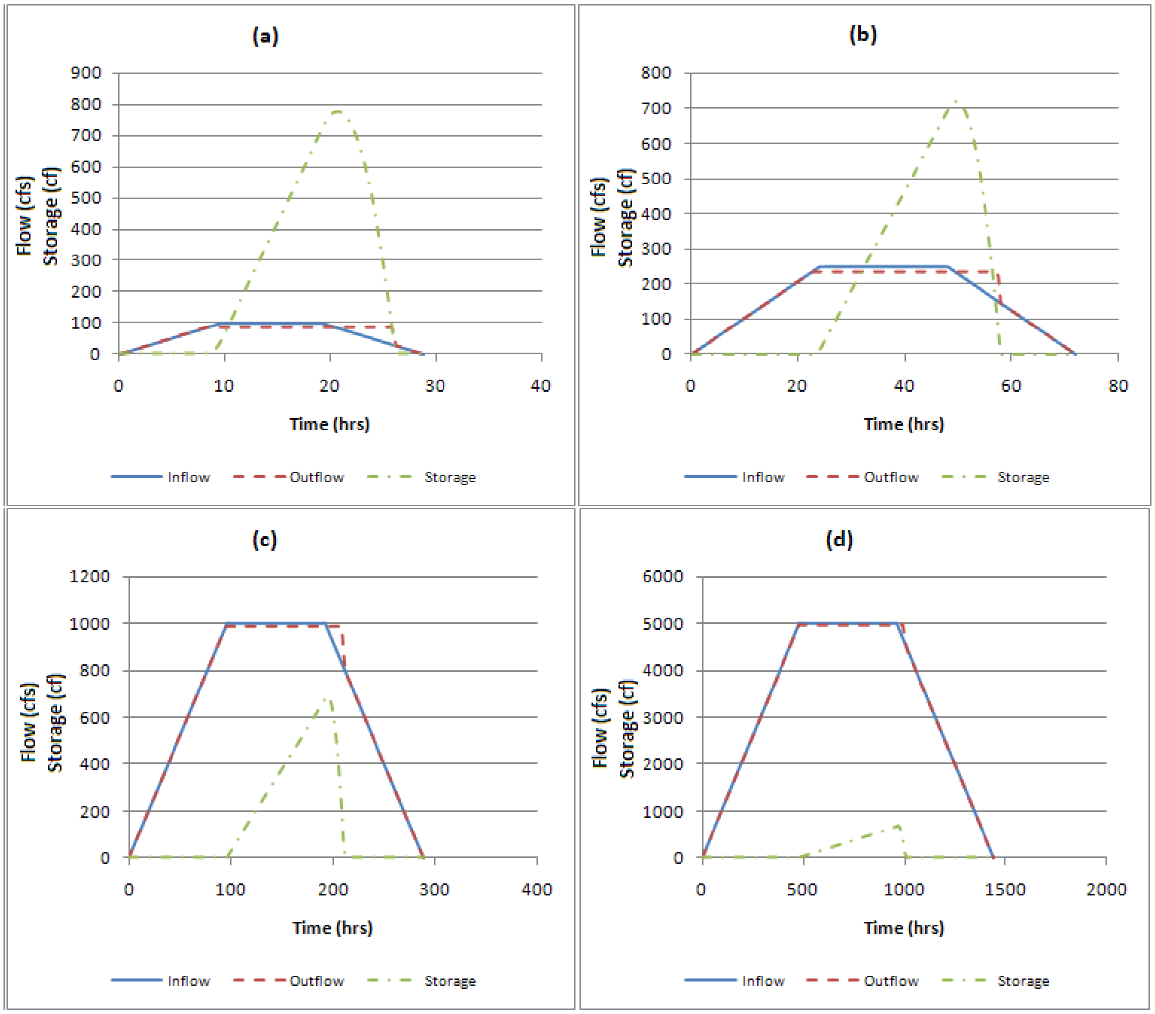

Figure 7. Inflow-outflow-storage plots for broad peak hydrograph 4 with Maximum Peak Reduction Rule; Δq_p=14 cfs

3.2.3 – Unregulated-Regulated Peak Flow Transform

An unregulated-regulated peak flow transform is constructed using peak inflows (unregulated) and outflows (regulated) for a range of scaled hydrographs. Figure 8 shows the transform using the Maximum Peak Reduction Rule. $Q_{p,out}$ is equal to 0 until $Q_{p,in}$ equals Δq_p, at which point the transform is a 1:1 line with $Q_{p,in}$ equal to $Q_{p,out}$. This transform assumes a perfect forecast of the hydrograph to determine how to operate the reservoir.

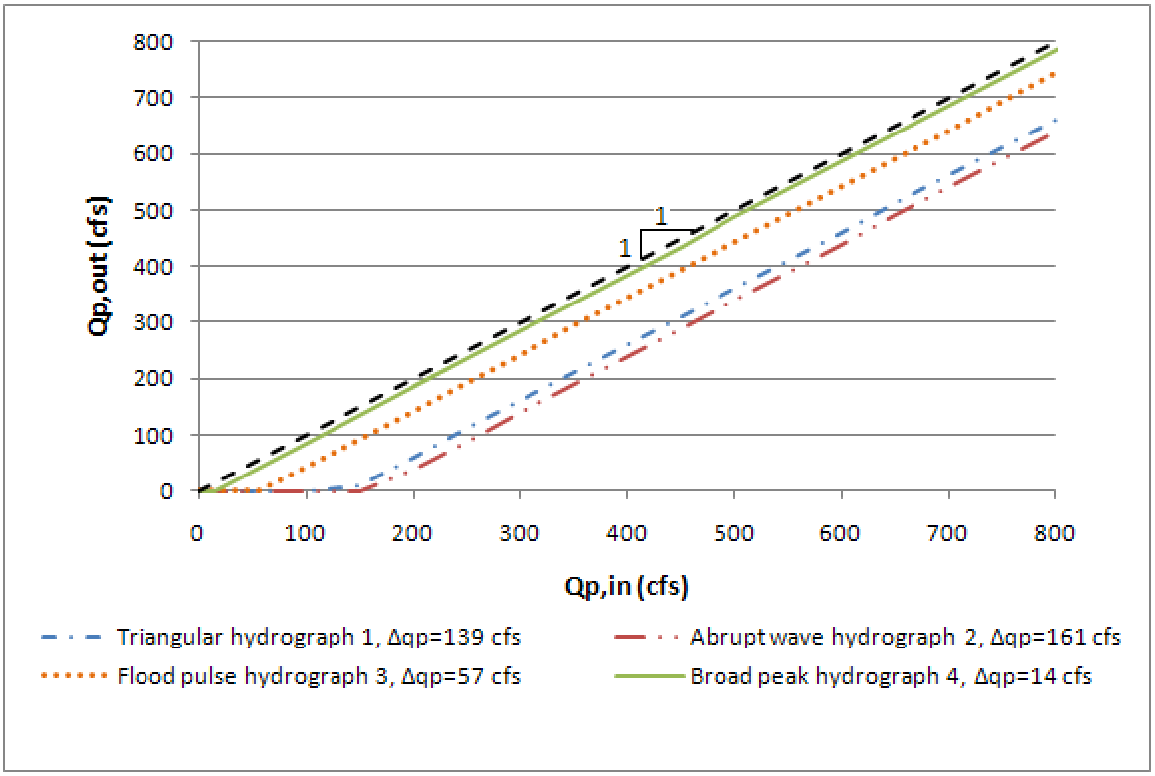

Figure 8. Peak flow transform with Maximum Peak Reduction Rule

3.3 – Minimize Exceedence of Downstream Channel Capacity Rule

With this second rule, when the inflow is less than the downstream channel capacity, all inflow is released. As inflow exceeds channel capacity, the reservoir begins to store the excess flow, releasing an outflow equaling the channel capacity. When the reservoir reaches its storage capacity, outflow again equals inflow. On the recession limb of the hydrograph, once the inflow is less than the downstream channel capacity, the reservoir begins to empty. Outflow equals the channel capacity until the flood pool is empty, at which time outflow again equals inflow.

This more common operating rule minimizes the downstream channel capacity exceedence during reservoir flood operations. This flood operating rule differs from the Maximum Peak Reduction Rule in that no hydrograph forecast exists, there is a downstream channel capacity, and the operator wants to minimize the flow exceeding this channel capacity. Following FEMA requirements on starting storages in reservoirs, 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). A downstream channel capacity of 150 cubic feet per second was used for illustrative purposes.

3.3.1 – Inflow-Outflow-Storage Plots

Operation of each hydrograph is examined with the downstream channel capacity rule. Figure 9 to Figure 12 illustrate the inflow, outflow, and storage in the reservoir for each hydrograph type and magnitude. For this theoretical derivation, a reservoir with a storage capacity of 2,788 cubic feet and a downstream channel capacity of 150 cfs was used. The four hydrographs were scaled by a large range of ratios for illustrative purposes only.

Figure 9 shows how a reservoir reduces the peak of triangular hydrograph 1 with the downstream channel operating rule. Outflow equals inflow until the downstream channel capacity is exceeded. Figure 9a illustrates a storm for which inflow never exceeds channel capacity, therefore outflow always equals inflow. As the hydrograph volume increases, the reservoir begins filling to capture the inflow that exceeds the downstream channel capacity. When the reservoir is full, outflow again equals inflow, as seen in the later portion of the hydrograph in Figure 9d. If the reservoir fills before the hydrograph's peak flow, there is no reduction in peak outflow, although the channel capacity exceedence is maximized, perhaps aiding downstream evacuation.

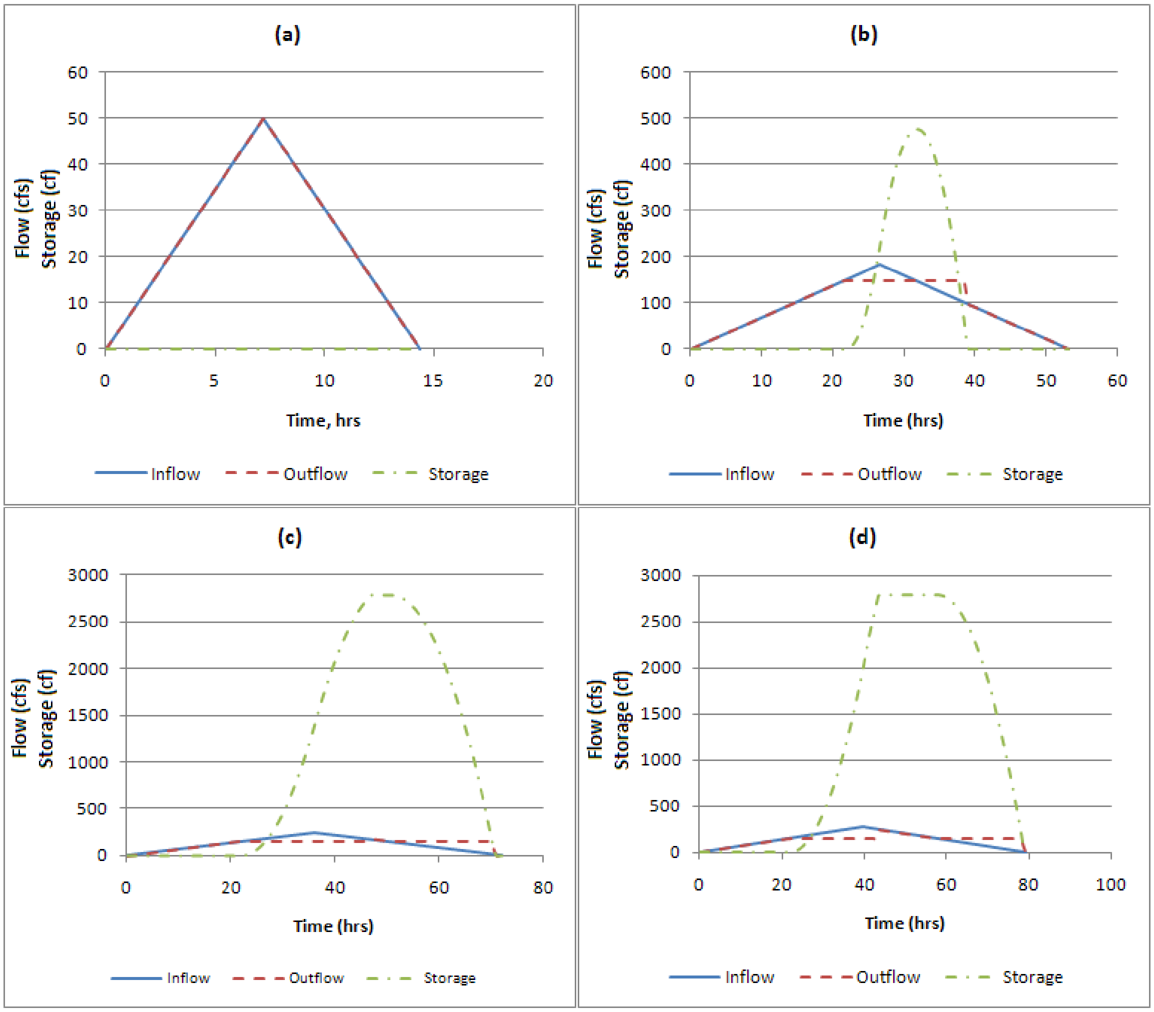

Figure 9. Inflow-outflow-storage plots for triangular hydrograph 1 with Downstream Channel Capacity Rule

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. With the abrupt flood, there is less concern that the reservoir will fill before the time of peak inflow. Reservoir operation with an abrupt hydrograph will always decrease the flood peak, although not necessarily optimally. Figure 10 illustrates this relationship as the abrupt wave volume increases. Figure 10a shows a hydrograph in which the downstream channel capacity is not exceeded and outflow equals inflow.

Figure 10b-c shows how the reservoir captures the peak and releases it later in the storm so as not to exceed downstream channel capacity. However, when the hydrograph is too large to allow capture of the entire peak, the reservoir must release the inflow despite exceeding downstream channel capacity, as in Figure 10d.

With an abrupt peak hydrograph the downstream channel capacity rule always produces both a delay and reduction in the outflow peak, even if the peak reduction is less than with peak minimizing operations.

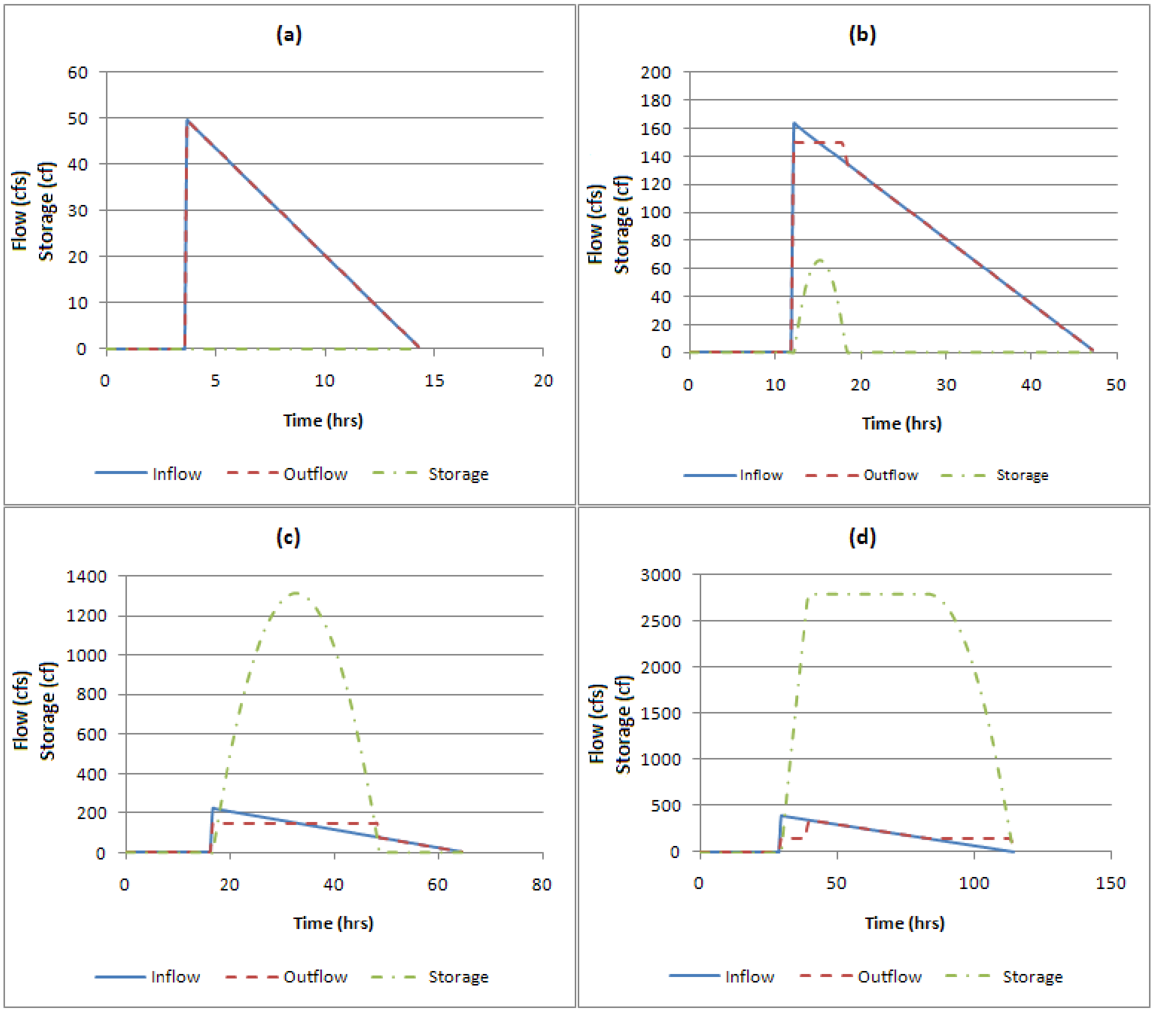

Figure 10. Inflow-outflow-storage plots for abrupt wave hydrograph 2 with Downstream Channel Capacity Rule

Figure 11 shows the inflow-outflow-storage plots for a flood pulse hydrograph 3. These are similar to that of the abrupt wave hydrograph since there is a sudden increase in flow. Reservoir storage is not needed when the storm is not large enough to exceed downstream channel capacity and outflow equals the inflow (Figure 11a). Figure 11b-c shows how the reservoir captures the peak and releases it later in the storm so as not to exceed downstream channel capacity. Figure 11d shows the case where the reservoir has reached capacity and must release the total inflow part way through the peak, as all storage has filled. If the reservoir fills before the end of the peak flow, the reservoir provides no decrease in the downstream peak, although it has delayed the onset of this peak flow and provided more time to evacuate downstream areas.

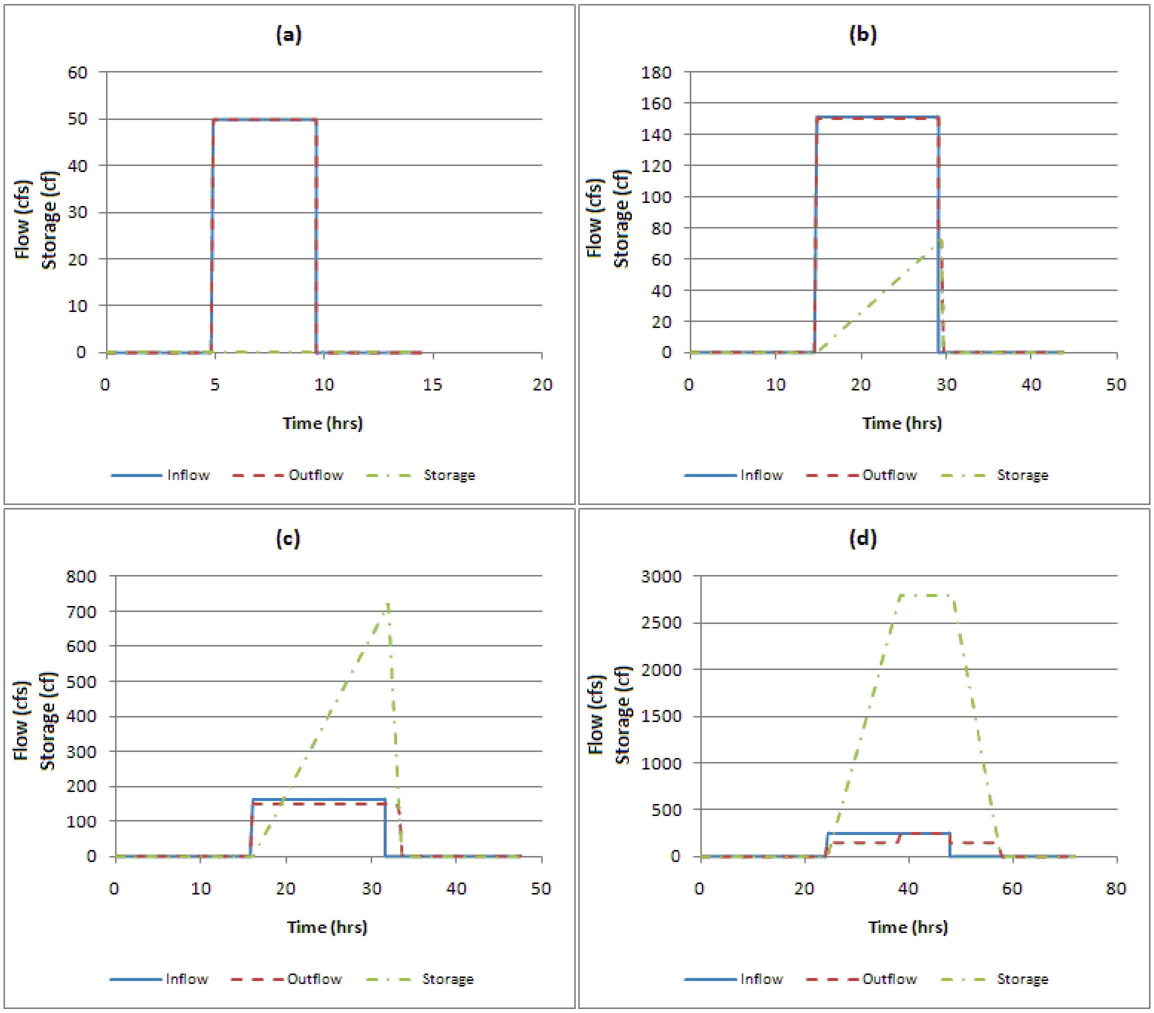

Figure 11. Inflow-outflow-storage plots for flood pulse hydrograph 3 with Downstream Channel Capacity Rule

Figure 12 illustrates broad peak hydrograph 4 as it is scaled up to capture a range of storms. As with the previous hydrographs, outflow equals inflow until the downstream channel capacity is exceeded or the reservoir is full. When the storm is not large enough to exceed downstream channel capacity, reservoir storage is not needed (Figure 12a). Figure 12b-c shows how the reservoir captures the peak and releases it later in the storm so as not to exceed downstream channel capacity Figure 12d shows the case in which the reservoir has reached capacity and must release all inflow. As with the pulse flood hydrograph, if the reservoir fills before the end of the peak flow, the reservoir provides no reduction in downstream peak, although it has delayed onset of the peak.

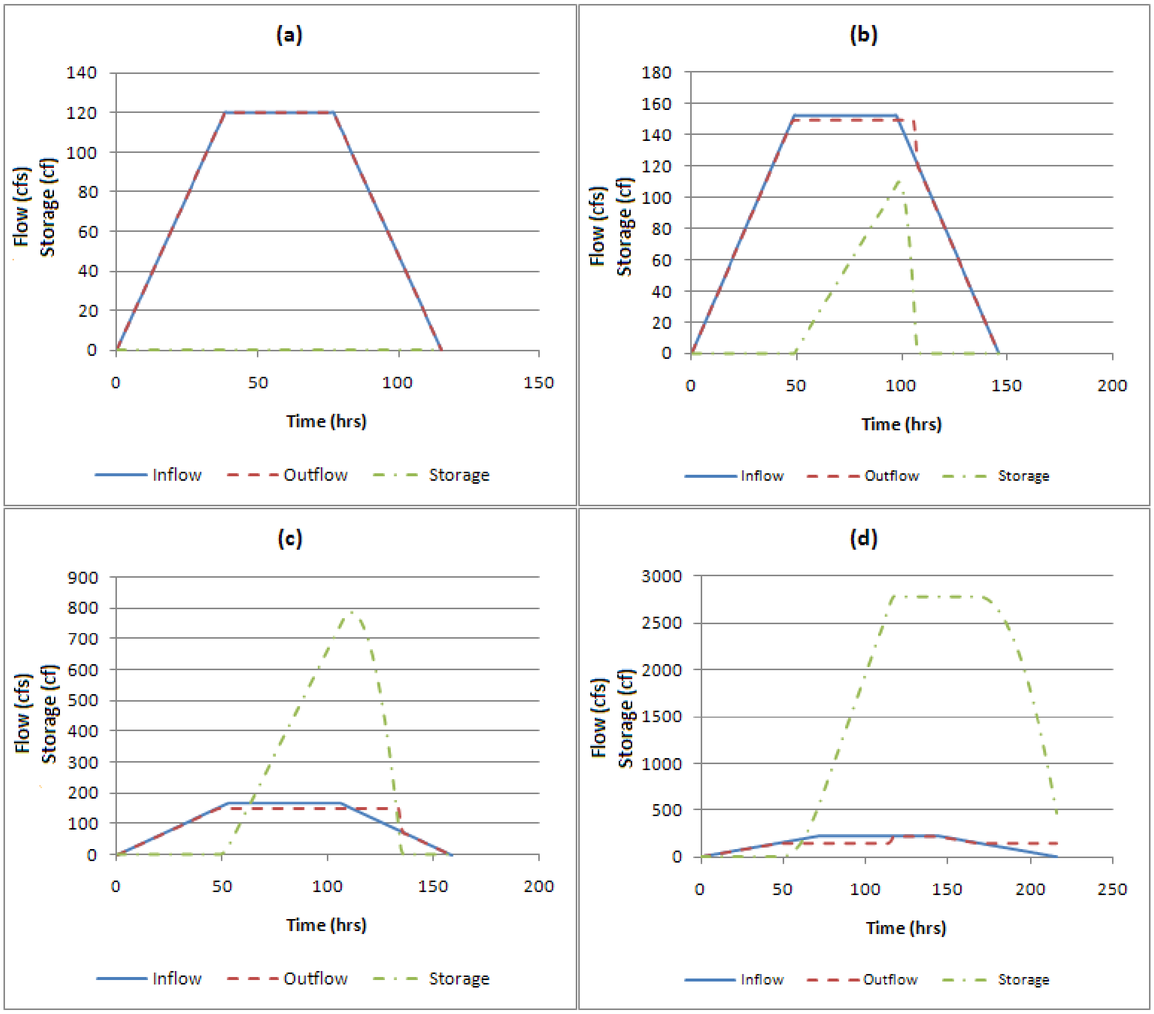

Figure 12. Inflow-outflow-storage plots for broad peak hydrograph 4 with Downstream Channel Capacity Rule

3.3.2 – Unregulated-Regulated Peak Flow Transform

The unregulated-regulated peak flow transform for the Downstream Channel Capacity Rule varies with the individual hydrograph because the reservoir reaches capacity at different times during the storm. The shape of the hydrograph determines how quickly the reservoir fills and whether outflow can be kept below the downstream channel capacity. Figure 13 illustrates the peak flow transforms for each of the four hydrographs. The transform follows the 1:1 line until the downstream channel capacity is reached and the reservoir begins to store the flows. A downstream channel capacity of 150 cfs was used for illustrative purposes. As the ability to capture the entire peak decreases, the peak flow transform curve moves towards the 1:1 line when inflow equals outflow.

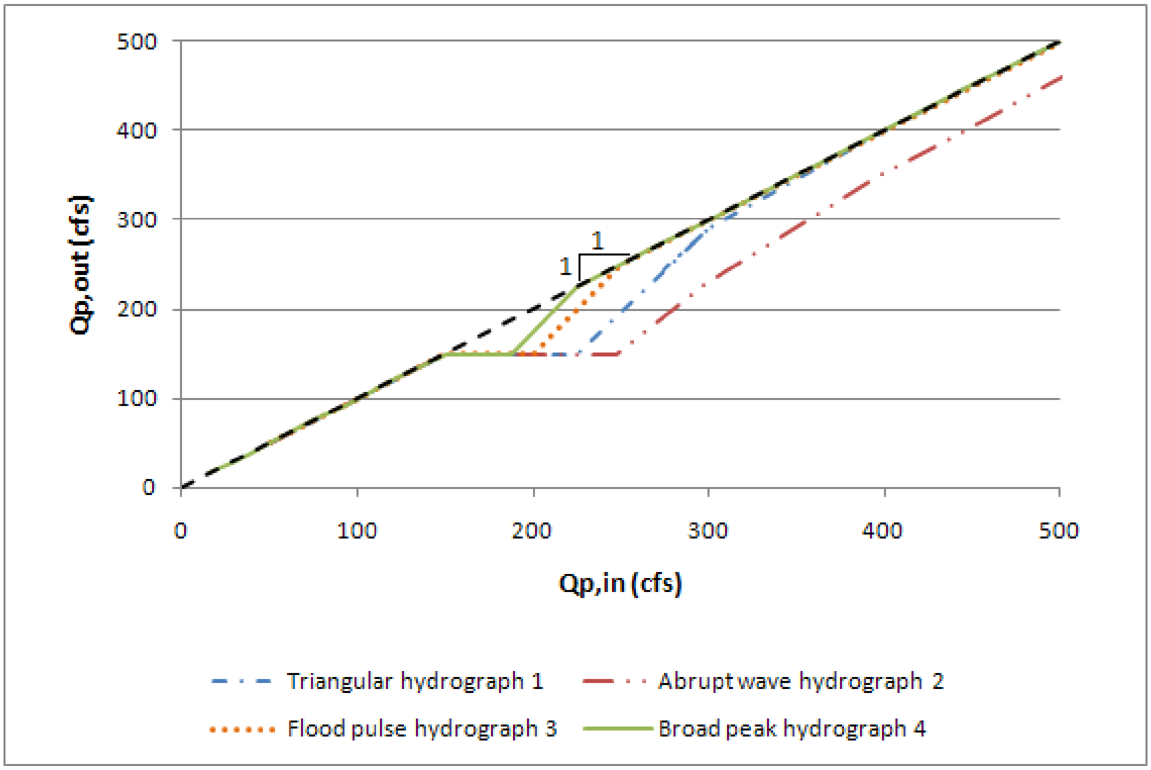

Figure 13. Peak flow transform with Downstream Channel Capacity Rule

3.4 – Peak Flow Transform Comparisons

This section compares the flow transforms for the four hydrographs, the two rules, and various sized reservoirs. Figure 8 illustrates the peak flow transform for the four hydrographs using the Maximum Peak Reduction Rule. As shown in Figure 8, $Q_{p,out}$ is zero until $Q_{p,in}$ is Δq_p, at which point the transform is a 1:1 line with $Q_{p,in}$ equal to $Q_{p,out}$. The shape of the hydrograph determines the value of Δq_p. The broad peak hydrograph 4 has the lowest value of Δq_p because each unit of peak reduction requires more use of storage capacity than the other hydrographs. This is similar for flood pulse hydrograph 3 because of the extended peak. The sudden wave of flow in hydrograph 2 causes its Δq_p to be larger than for the steady increase in flow for hydrograph 1.

Figure 13 illustrates the flow transform for the four hydrographs using the Downstream Channel Capacity Rule. As with the Maximum Peak Reduction Rule, the more difficult it is to capture the entire peak of the storm, the closer the transform curve will be to the 1:1 line representing when peak inflow equals peak outflow. The hydrographs that can be best captured will have more points on the transform with $Q_{p,out}$ less than $Q_{p,in}$. Each transform eventually converges with the 1:1 line as the hydrograph overwhelms the storage capacity before the peak inflow is reached.

Figure 14 shows the effects of the different rules on the flow transform. The Maximum Peak Reduction Rule is labeled “MPRR” and the Downstream Channel Capacity Rule is labeled “DCCR”. The Maximum Peak Reduction rule provides the optimal flow transform as it extends away from the 1:1 line over the entire range of inflow, but requires foreknowledge of the flood hydrograph. The Downstream Channel Capacity Rule is most favorable for smaller floods. The reservoir is only able to capture the peak before reaching capacity for smaller floods or an instantaneous peak, similar to the abrupt wave hydrograph 2. For larger, longer floods, the reservoir fills before the peak and the reservoir is forced to release the entire incoming peak above channel capacity. After this point, outflow equals inflow and the transform follows the 1:1 line, except for the abrupt wave where the peak occurs at the storm's beginning.

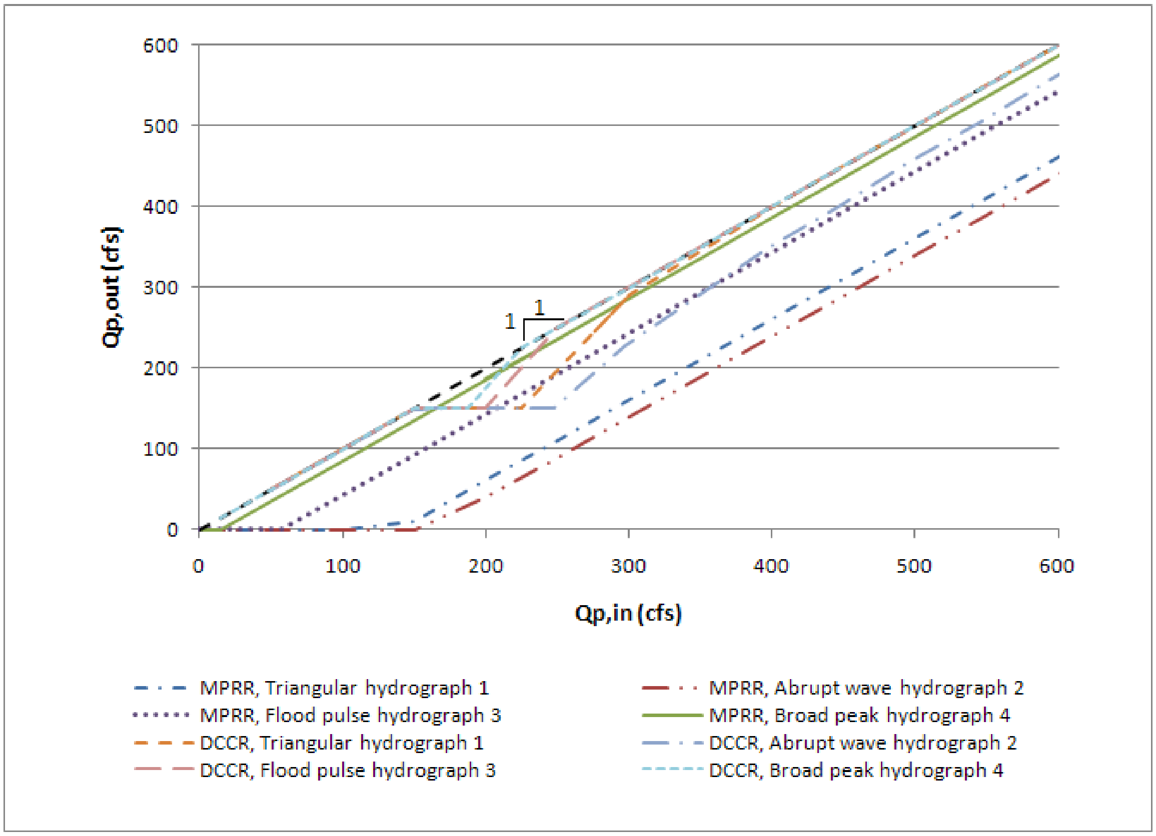

Figure 14. Comparison of peak flow transforms for both operating rules

The effect of different reservoir sizes on the inflow-outflow peak transform is shown for the four hydrographs. Figure 15 shows the results for the Maximum Peak Reduction Rule and the Downstream Channel Capacity Rule for each hydrograph and Figure 16 compares the rules on one plot for each hydrograph. A small reservoir offers inadequate storage space to capture Δq_p and the peak of the storm, so $Q_{p,out}$ roughly equals $Q_{p,in}$. A large reservoir can capture a larger peak and allow $Q_{p,out}$ to be less than $Q_{p,in}$ for part of the transform. The broad peak hydrograph 4 is the least effectively at captured because its longer peak duration produces more volume and therefore requires more storage capacity per unit of peak reduction.

Reservoirs operating for flood control aim to decrease regulated outflows during peak storm events. Therefore, regulated peak flows should not exceed unregulated peak flows on the curve. At times of low flow and high flow, the curve may have a 1:1 slope when outflow equals inflow and regulation is either unnecessary or unattainable.

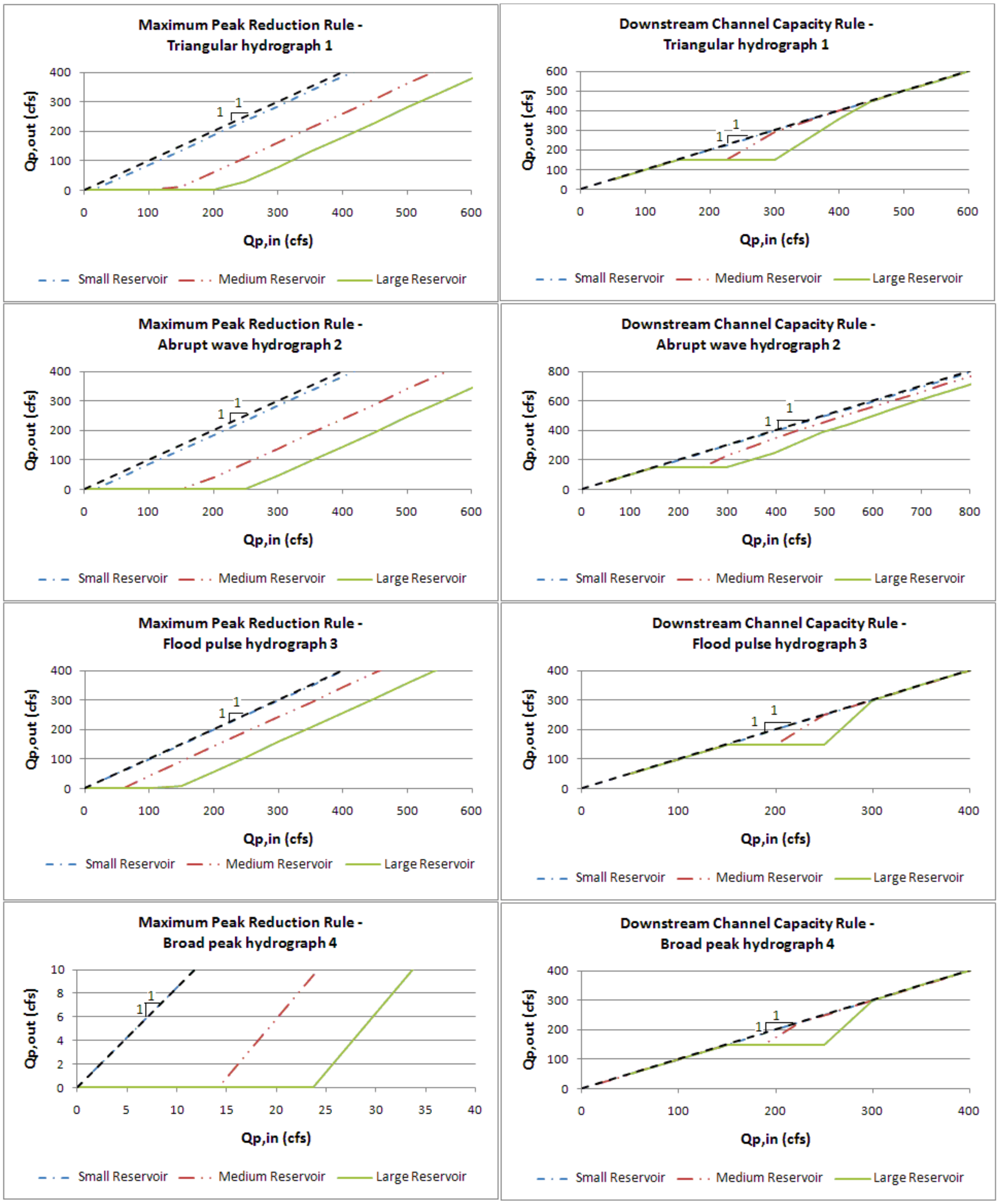

Figure 15. Peak flow transforms for various size reservoirs

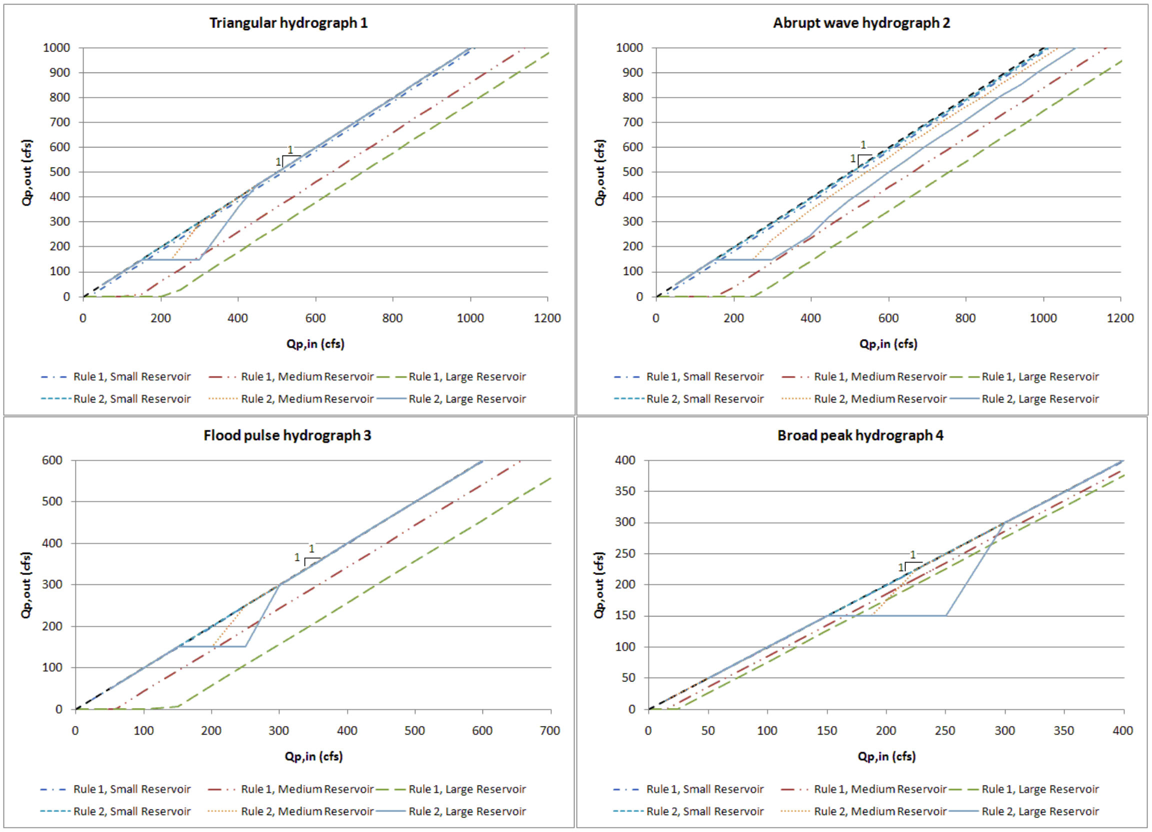

Figure 16. Peak flow transforms for various size reservoir for each hydrograph

The theory discussed above is now compared to an empirical case study at the Feather River-Yuba River confluence where a regulated frequency curve is developed using an empirical peak flow transform.

Chapter 4.0 – Case Study: Feather River Watershed

[Disclaimer: Figures in this report are for illustrative purposes only. Data, models, and results have been simplified to illustrate key concepts related to this paper.]

The Yuba- Feather river watershed is illustrated in Figure 17. The total watershed size is 6,264 miles to the confluence with the Sutter Bypass. This includes 5,365 miles at the Feather-Yuba confluence. The two flood control reservoirs in the system are Oroville Reservoir and New Bullards Bar Reservoir (USACE 2009).

Oroville Dam and Reservoir are a unit of the Feather River Project, part of the California State Water Project. Oroville Dam is on the Feather River, a tributary of Sacramento River, about 6 miles upstream from the town of Oroville. It was built for water supply, flood control, power generation, recreation, and conservation. It includes 750,000 acre-feet of flood control storage space to protect the cities of Marysville, Yuba City, Oroville and other smaller communities. Oroville Reservoir gross pool capacity is 3,538,000 acre-feet (USACE 1970).

The New Bullards Bar Dam and Reservoir are on the Yuba River which flows into the Feather River. It was built for flood control, conservation, power generation, water supply, and recreation. It has 170,000 acre-feet of flood control storage space and a gross pool capacity of 960,000 acre-feet (USACE 1972).

Both Oroville Reservoir and New Bullards Bar Reservoir operate within flood limits defined in their water control manuals (USACE 1970, USACE 1972). These flood-related limits include:

- Maximum downstream channel capacity at dam
- Maximum downstream channel capacity at various locations, including Yuba City, Marysville, and the confluence
- Maximum rate of flow increase
- Maximum rate of flow decrease

Chapter 4.1 – Feather River below the Confluence with the Yuba River

This case study focuses on developing a regulated frequency curve on the Feather River below the confluence with the Yuba River. Figure 18 is a schematic of the Yuba-Feather river watershed. The point of interest is labeled “FR+YR Junction”.

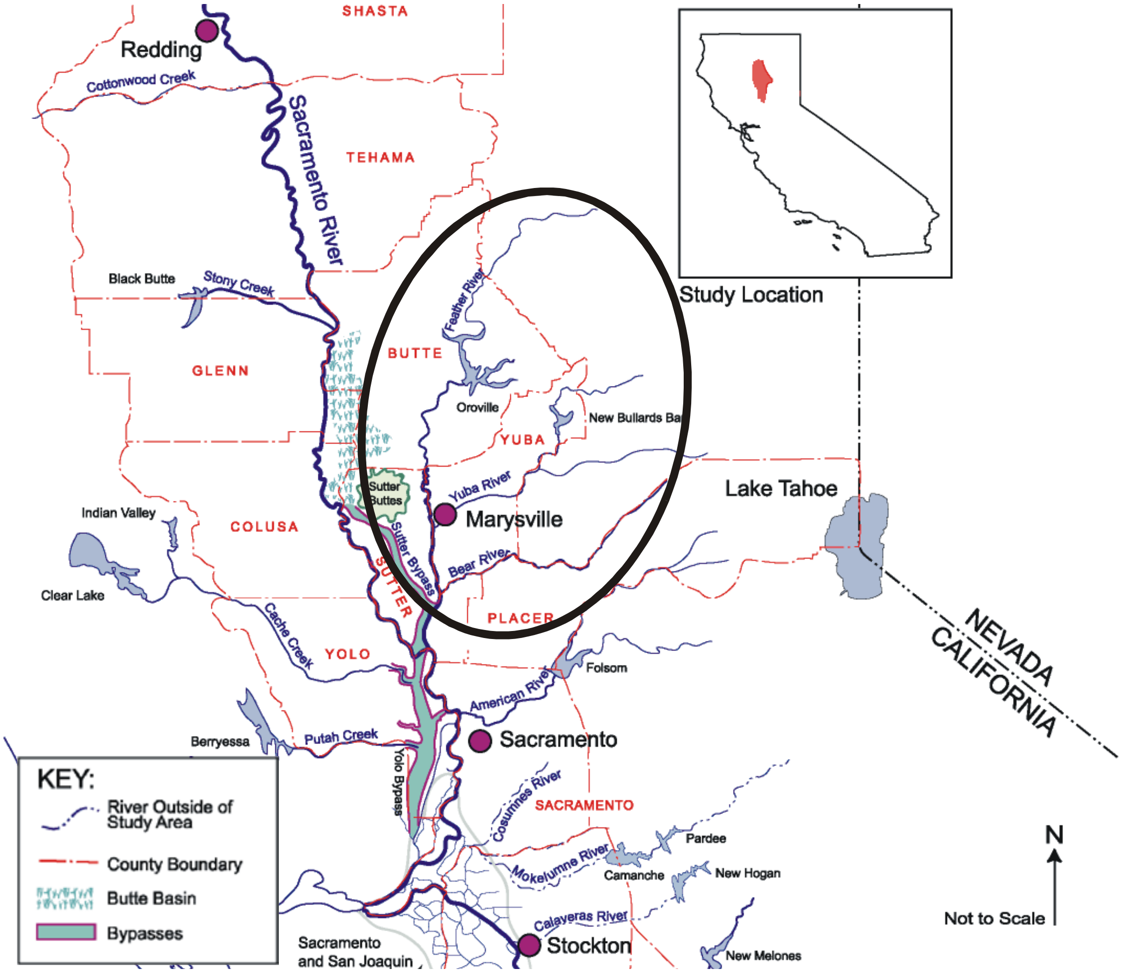

Figure 17. Yuba-Feather System (adapted from Sacramento and San Joaquin Comprehensive Study documentation)

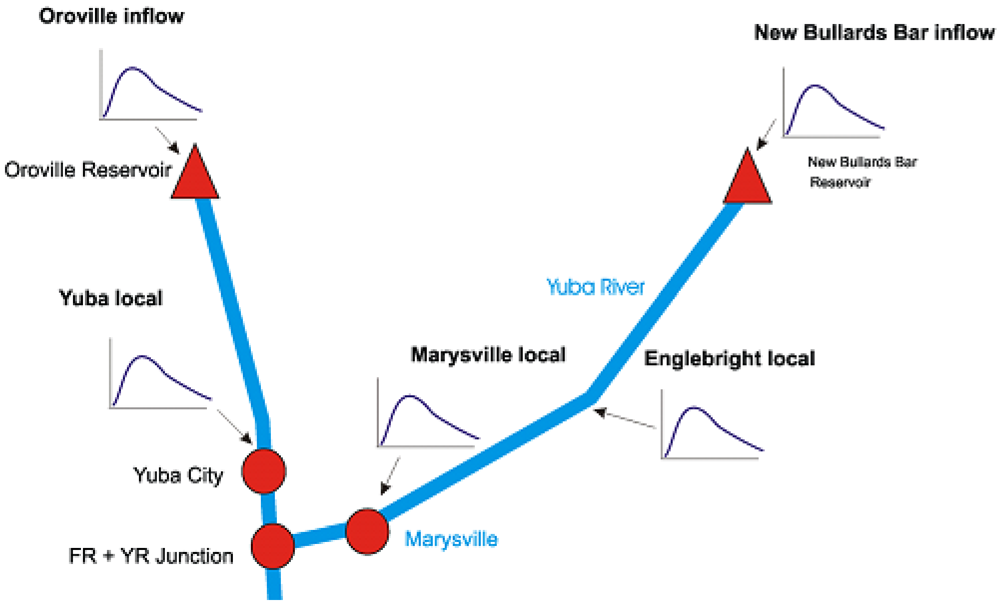

Figure 18. Yuba-Feather system modeling schematic (adapted from Illustrative Example, USACE 2009)

The Hydrologic Engineering Center's Reservoir Simulation (HEC-ResSim) program is used to route gage data through the system to develop the unregulated and regulated flow time series at the Feather River below the confluence with the Yuba River. HEC-ResSim was developed by the U.S. Army Corps of Engineers and is the successor to "HEC-5, Simulation of Flood Control and Conservation Systems" program. HEC-ResSim includes of a graphical user interface, a computational program to simulate reservoir operation, data storage and management capabilities, and graphics and reporting facilities (USACE 2007). It is used to model reservoir operations at one or more reservoirs whose operations are defined by a variety of operational goals and constraints.

Two routing models were configured using HEC-ResSim to represent the following two cases within the Yuba Feather system, 1) an unregulated model (storage associated with reservoirs and overbank areas is absent); and 2) a regulated model, which includes the effects of hydraulic structures, operable weirs and diversions, as well as the effects of levees. Figure 19 illustrates the effect of regulation on the 1997 flow time series at the Feather River below the confluence with the Yuba River. The peak flow is reduced by storing water in the reservoir and releasing it later in the storm.

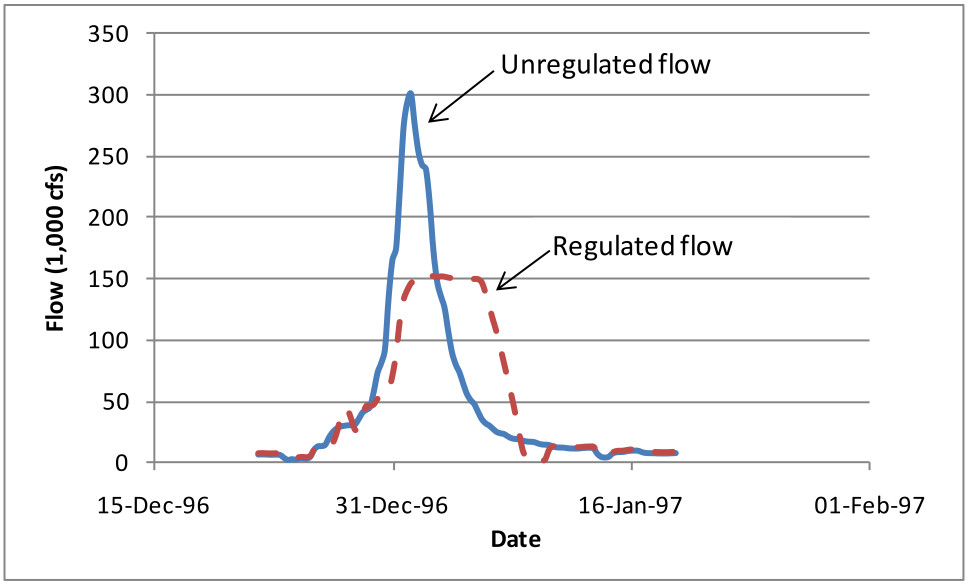

Figure 19. Illustration of unregulated and regulated Feather River flows at the Feather River below the confluence with the Yuba River

Using the unregulated flow time series from the reservoir routings and procedures from Bulletin 17B (IACWD 1982), the unregulated flow frequency curve is developed by extracting the annual maximum unregulated flows at the Feather River below the confluence with the Yuba River. The procedures in EM 1110-2-1415 (USACE 1993) are used to compute the unregulated frequency curves for the 1-, 3-, 7-, 15-, and 30-day annual maximum volumes. These curves are shown in Figure 20.

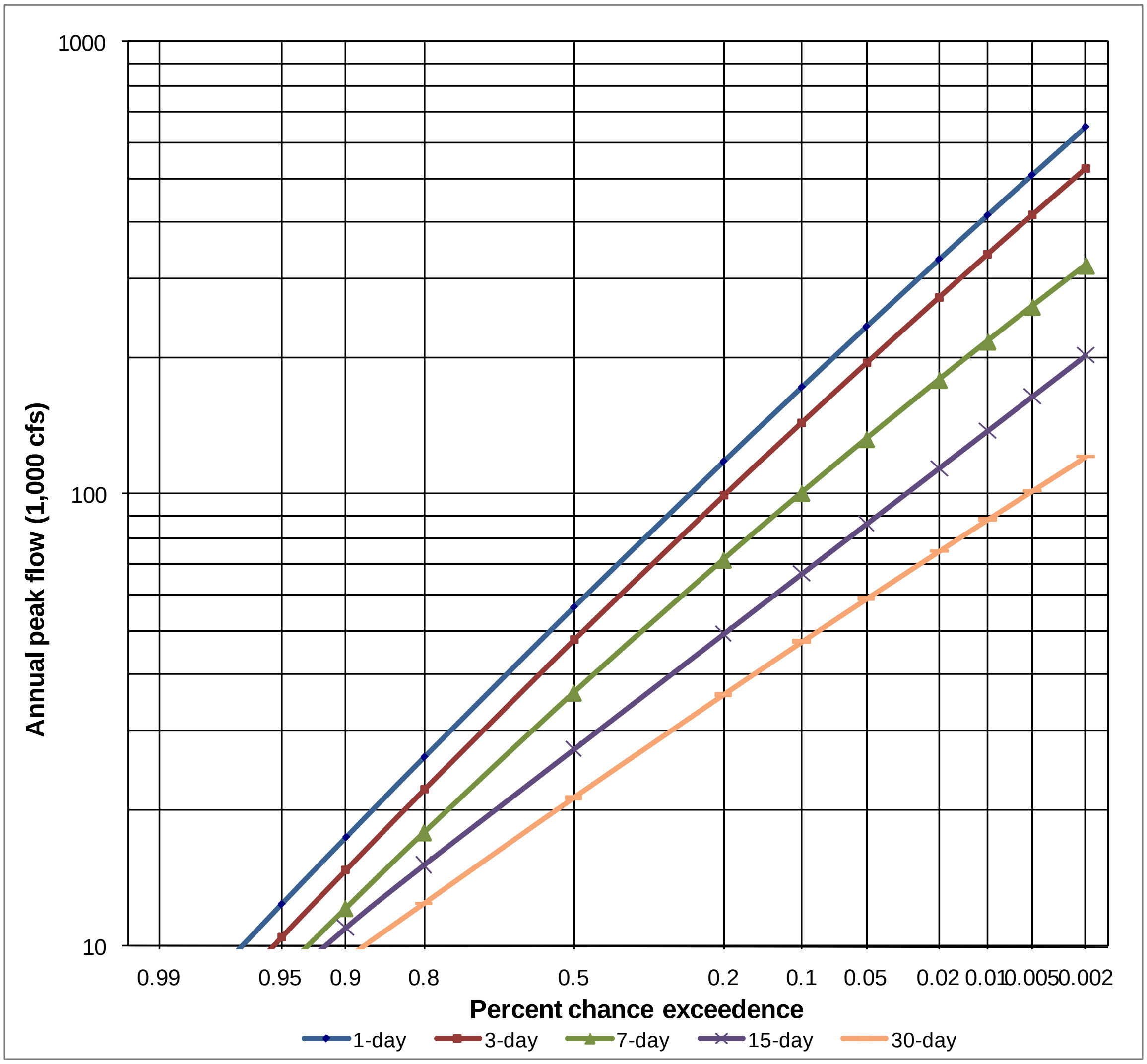

Figure 20. Illustration of unregulated volume frequency curves at the Feather River below the confluence with the Yuba River

To develop the regulated flow frequency curve, an unregulated-regulated relationship is needed. An important step is finding the critical unregulated flow duration that best matches the regulated peak flow. This is found by routing various historical events at the confluence and using a rank-based correlation statistic such as Kendall's tau or Spearman' rho (Helsel and Hirsch 2002). This correlation statistic identifies which unregulated flow duration has the highest correlation with the regulated peak flow. This duration would be the critical duration. The Feather River below the confluence with the Yuba River has a 3-day critical duration. Therefore, the 3-day unregulated flow volumes and peak regulated flows are used to develop the peak flow transform, shown in Figure 21. Each point on the transform represents one 3-day unregulated flow volume and its corresponding peak regulated flow, as determined with the two HEC-ResSim models representing the regulated and unregulated systems. There are a number of points in the lower part of the curve where outflow peaks exceed inflow peaks. These are below the flood range of flows and are irrelevant for this purpose. Regulation stores the peak of the hydrograph and oftentimes extends the length of the event. This causes the regulated average peak to be larger than the unregulated peak.

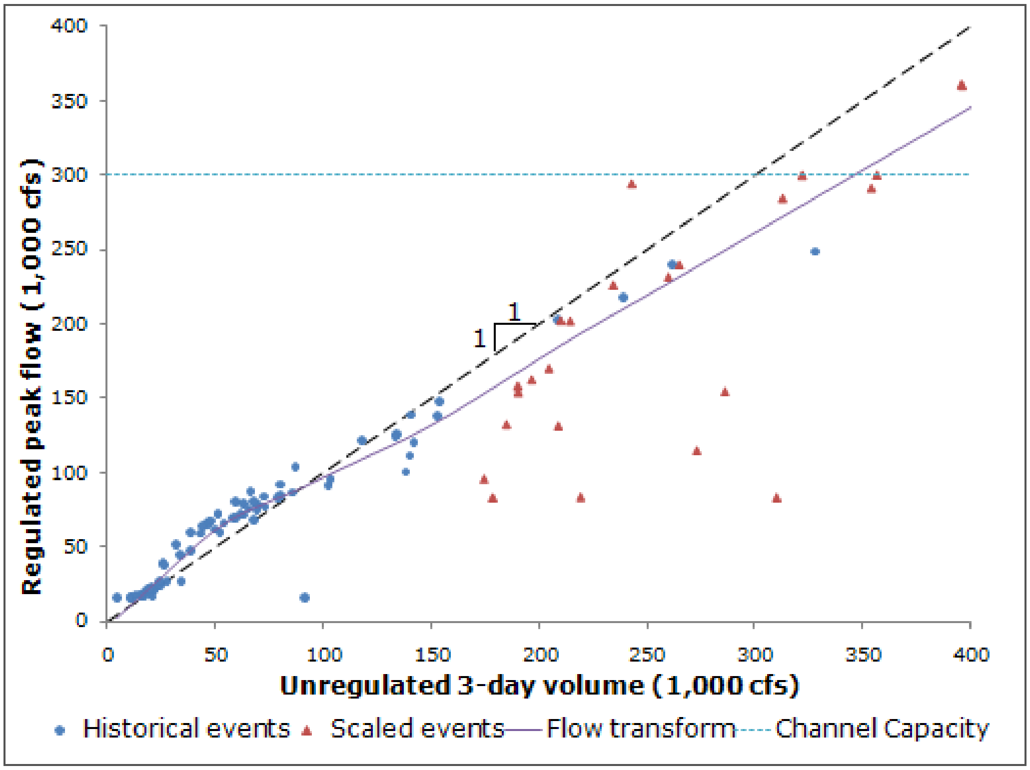

Figure 21. Illustration of unregulated-regulated flow transform curve at the Feather River below the confluence with the Yuba River (adapted from USACE 2009)

Historical data is rare for the larger events (e.g. p=0.002) which are the most critical in defining the upper end of the unregulated-regulated relationship. These large hypothetical flood events are estimated by scaling the large storm events by a factor of 2 or 3 and routing them through the reservoir model, consistent with the guidance in EM 1110-2-1415 (USACE 1993). These points are labeled as scaled events in Figure 21. These scaled events will likely stress the system at and beyond design flows.

The paired values of unregulated and regulated flows are used to fit the unregulated-regulated flow transform curve. This curve translates an unregulated flow to the corresponding regulated flow, so the regulated flow frequency curve is sensitive to the shape and fit of this curve. One method for fitting the curve to the unregulated-regulated dataset is a robust locally weighted scatterplot smoothing (LOWESS, also known as robust locally weighted regression). LOWESS is a method in which a polynomial is fit to the data using weighted least squares. The fitted values are computed by using the “nearest neighbor routine” and robust locally weighted regression of degree 1 with the tricube weight function. The robust fitting procedure guards against deviant point distorting the smoothed points (Cleveland 1979). Results of this method are illustrated in Figure 21.

Aspects of the theoretical peak flow transforms analyzed earlier in this paper are not entirely evident in the empirical transform in Figure 21. The transform begins near point 0,0, conflicting with the Maximum Peak Reduction Rule where the transform would begin when $Q_{p,in}$ is Δq_p and then follow along a 1:1 line. When comparing with the theoretical peak flow transforms derived using the Downstream Channel Capacity Rule, the transform does not have a definitive divergence from the 1:1 line at the downstream channel capacity, which is 300,000 cfs for the Feather-Yuba confluence. The variation from the theoretical peak flow transform is mainly due to the complexity of the system and the LOWESS curve fit. The HEC-ResSim models did not have a hydrograph forecast available and the reservoirs are operating for more than just a downstream channel capacity.

The flow transform in Figure 21, along with the 3-day unregulated flow frequency curve in Figure 20, is used to develop the regulated frequency curve for the Feather River below the confluence with the Yuba River. The curve is constructed one point at a time using the following steps and is illustrated in Figure 22.

1. An unregulated peak flow (or volume) is established for a specified probability using the unregulated flow frequency curve.
2. This unregulated peak flow (or volume) is then used to obtain the corresponding regulated peak flow using the peak flow transform curve.
3. The specified probability used in step 1 and the regulated peak flow found in step 2 define one point on the regulated frequency curve.
4. This process is continued for a range of probabilities to define the regulated peak flow frequency curve.

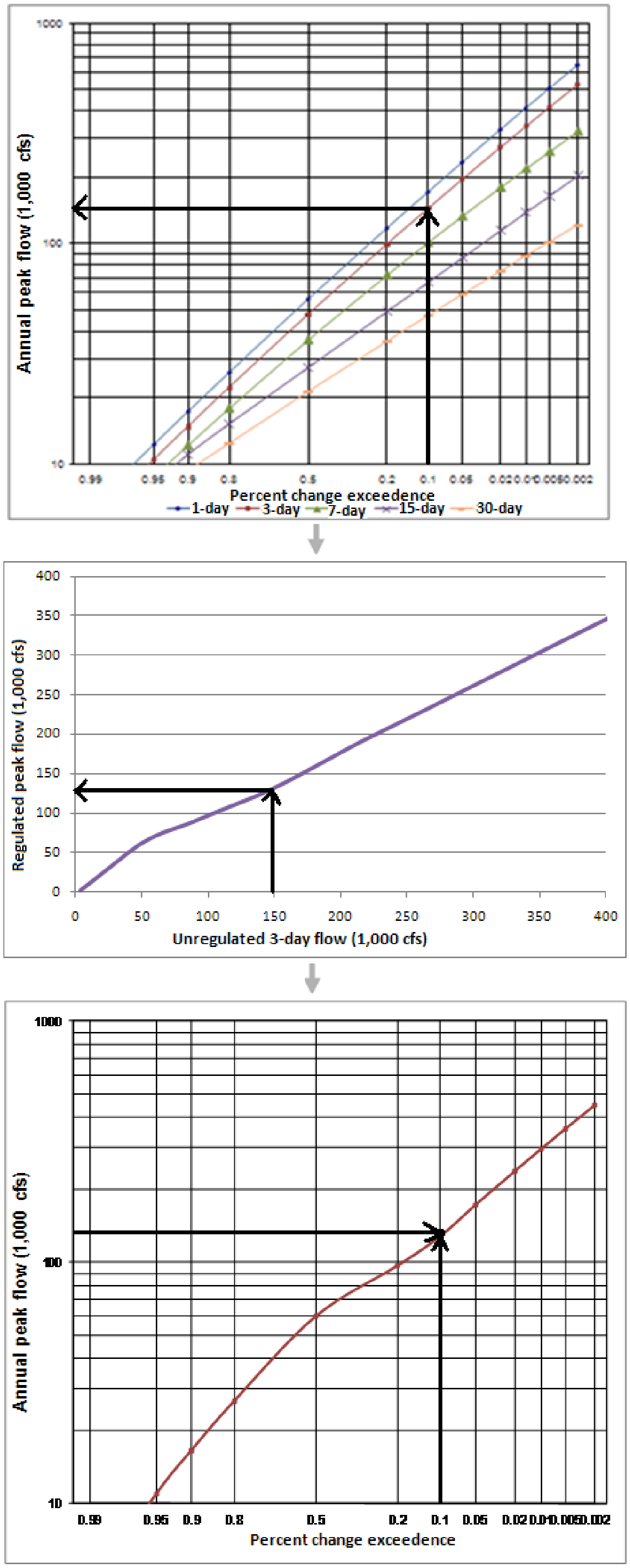

Figure 22. Development of the regulated outflow frequency curve

The resulting regulated frequency curve for the Feather River below the confluence with the Yuba River is shown in Figure 23 along with the unregulated frequency curve, for comparison. When the regulated flows are less than the unregulated flows, regulation is either unnecessary or unattainable. For smaller more frequent storms, regulation is unnecessary. The point at which the two curves cross near 10,000 cfs is when regulation becomes effective within the system. When the two curves cross again near 100,000 cfs, for the larger less frequent storms, regulation is unattainable.

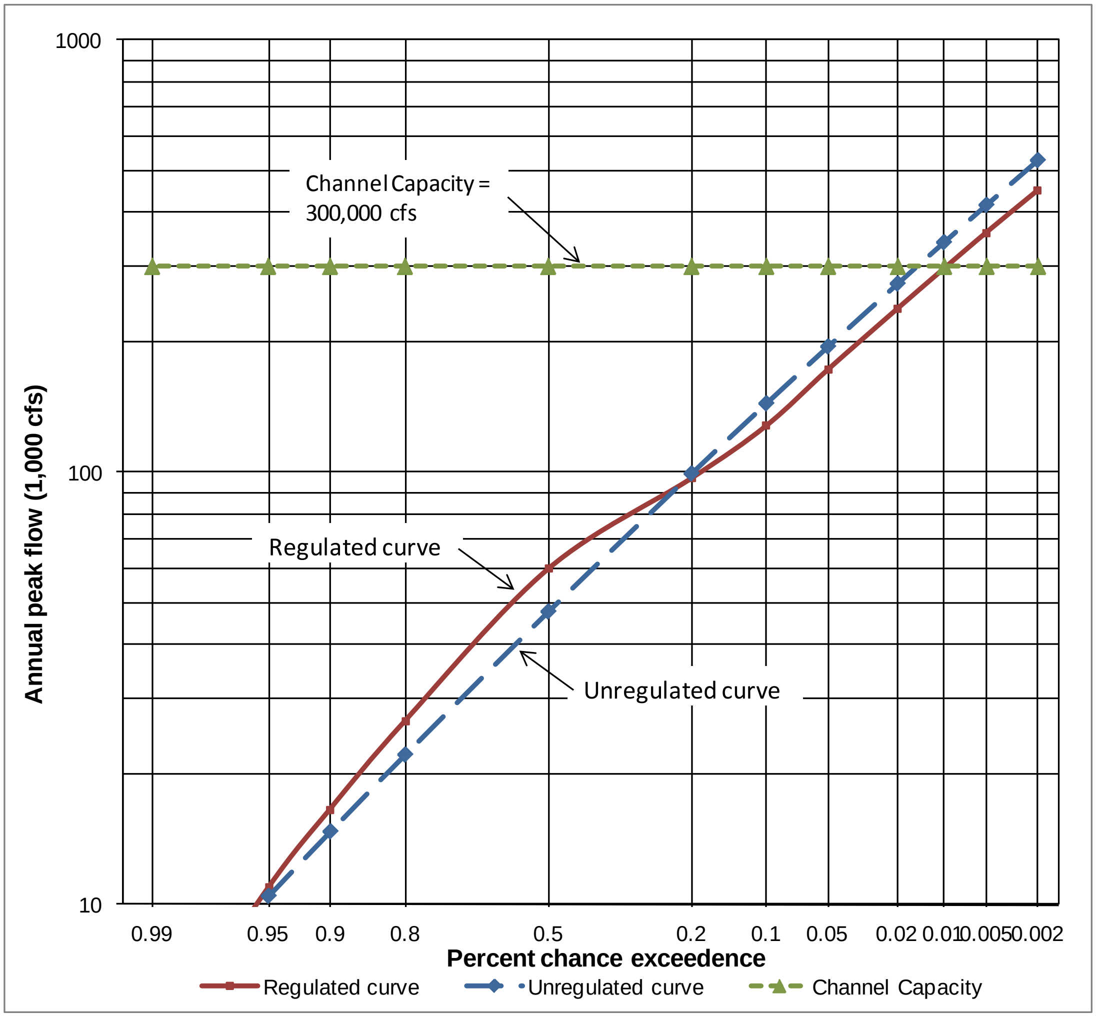

Figure 23. Illustration of frequency curves for the Feather River below the confluence with the Yuba River

Chapter 4.2 – Feather River above the Confluence with the Yuba River

This case study illustrates a peak flow transform for the Feather River above the confluence with the Yuba River. The point of interest is labeled “Yuba City” in Figure 18.

Similar to the previous case study, two routing models were configured using HEC-ResSim to represent the following two cases within the Yuba Feather system, 1) an unregulated model (storage associated with reservoirs and overbank areas is absent); and 2) a regulated model, which includes the effects of hydraulic structures, operable weirs and diversions, as well as the effects of levees.

Using a rank-based correlation statistic, an unregulated flow duration of one day was found to have the highest correlation with the regulated peak flow. Therefore the Feather River above the confluence with the Yuba River has a 1-day critical duration. The 1-day unregulated flow volumes and peak regulated flows are used to develop the peak flow transform, shown in Figure 24. Each point on the transform represents one 1-day unregulated flow volume and its corresponding peak regulated flow, as determined with the two HEC-ResSim models representing the regulated and unregulated systems.

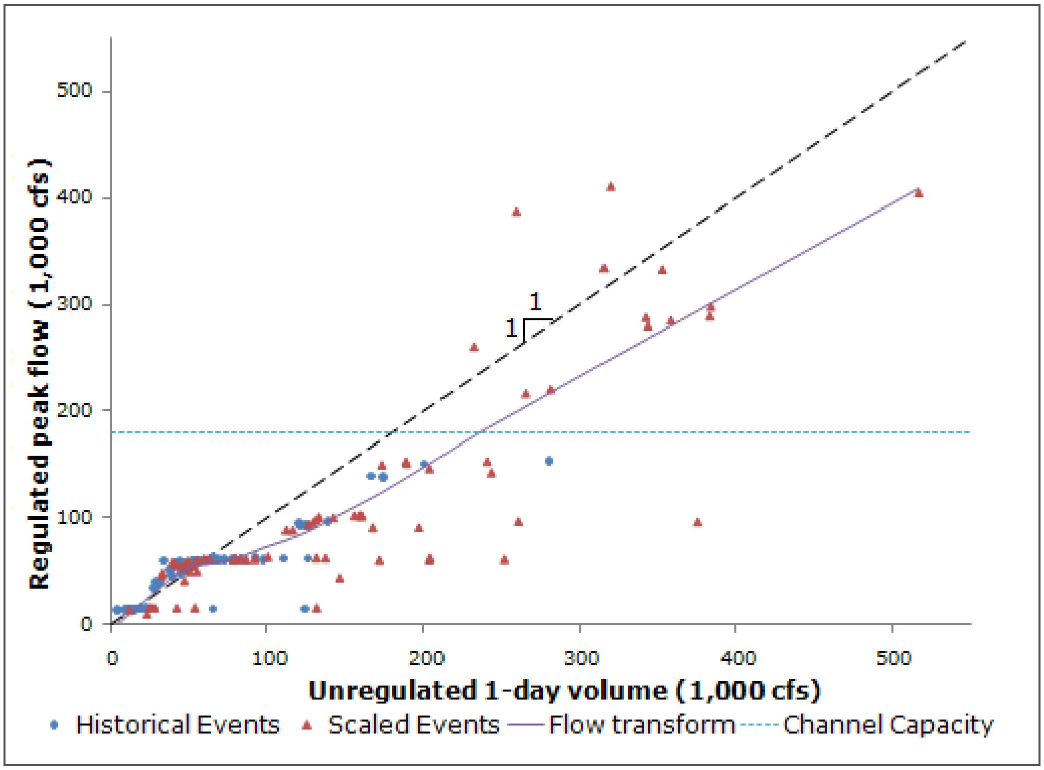

Figure 24. Illustration of unregulated-regulated flow transform curve at the Feather River above the confluence with the Yuba River

The theoretical peak flow transforms analyzed earlier in this paper are more evident in this case study. The peak flow transform shown in Figure 24 is most similar to the Downstream Channel Capacity Rule. The Downstream Channel Capacity Rule is seen as the transform in Figure 24 deviates from the 1:1 line as the reservoir stores some of the storm volume. The transform does not diverge from the 1:1 line at the downstream channel capacity, 180,000 cfs for Yuba City, but instead near 60,000 cfs. The theoretical peak flow transforms analyzed earlier in this paper assumed an empty reservoir and only a downstream channel capacity rule, whereas the transform in Figure 24 represents a complex operating system and a LOWESS fit curve. Because of the storage capacity within the system, the transform does not completely return to the 1:1 line (when outflow equals inflow). A larger storm event would need to be modeled to show this, however routing a storm this large would not be reasonable.

Chapter 4.3 – Effects of Critical Duration on the Peak Flow Transform

Finding the critical unregulated flow duration that best matches the regulated peak flow is an important step in developing a peak flow transform. Reservoir regulation reduces the peak storm by storing the highest inflows for release later. To account for this in developing a regulated frequency curve, the peak flow transform does not compare the day-to-day averages but rather the annual critical peak durations (e.g., 1-day, 3-day, 7-day). The annual critical peak duration of the inflow hydrograph greatly affects the outflow peak. Without regulation, the regulated peak equals the unregulated peak, and the critical duration is irrelevant. As upstream storage increases, the critical duration lengthens because reservoir storage attenuates the inflow peaks and causes the inflow volume to have a greater effect on the downstream peak flow (USACE 2009). As the effects of regulation lessen, critical duration should decrease.

The Feather-Yuba watershed case study used Kendall's tau statistic, a rank-based correlation statistic, to identify which unregulated flow duration has the highest correlation with the regulated peak flow. Table 1 and Table 2 show the results of the Kendall rank correlation, the root mean square error (RMSE) for peak outflows greater than 100,000 cfs, and the resulting critical duration for each location. Although there is not a large difference in the Kendall's tau statistic between unregulated flow durations, the higher value is the critical duration and has the strongest correlation with the regulated peak flows. The RMSE quantifies the difference between the peak flow transform functions and the modeled outflows and was calculated for peak outflows greater than 100,000 cfs. The lowest RMSE also coincides with the critical duration for each location. The Feather River below the confluence with the Yuba River has a 3-day critical duration and the Feather River above the confluence with the Yuba River has a 1-day critical duration. The longer critical duration below the confluence is representative of the increase in regulation due to more storage capacity between the two reservoirs in the system. The Feather River above the confluence also has unregulated local flows entering the system, resulting in a 1-day critical duration.

Table 1. Statistics of the peak flow transform for the Feather River below the confluence with the Yuba River

Unregulated flow duration (1)	**Kendall's tau statistic (2)**	**Root mean square error (cfs) (3)**
1-day	0.8609	75,241
3-day	*0.8637*	*71,322*
7-day	0.8277	81,620

Critical duration is italicized.

Table 2. Statistics of the peak flow transform for the Feather River above the confluence with the Yuba River

Unregulated flow duration (1)	**Kendall's tau statistic (2)**	**Root mean square error (cfs) (3)**
1-day	*0.8204*	*60,280*
3-day	0.7969	60,394
7-day	0.7523	72,217

Critical duration is italicized.

Figure 25 demonstrates the variation of the peak flow transform curve using different unregulated flow durations for the Feather River below the confluence with the Yuba River. The critical duration is a 3-day unregulated flow for this location in the system. Using an unregulated flow duration other than the critical duration, such as the 1-day or 7-day, for the peak flow transform will affect the peak regulated frequency curve.

Figure 26 shows the sensitivity of the peak regulated frequency curves developed using a 1-day, 3-day, and 7-day unregulated flow duration for the Feather River below the confluence with the Yuba River. The critical duration is a 3-day unregulated flow for this location in the system. The peak regulated frequency curve developed using the 3-day unregulated flow duration accurately represents the system. Figure 26 shows that the peak regulated frequency curve becomes most sensitive to the critical duration for flood events greater than the 10-year (p=0.1) event. A peak regulated frequency curve that accurately quantifies the larger less frequent events is important for flood protection, and is determined using only the critical duration. The peak regulated frequency curve developed using the 7-day unregulated flow duration underestimates the peak regulated flow for these events. The peak regulated frequency curves shown in Figure 26, developed using unregulated flow durations other than the critical duration of 3 days, are the results of a sensitivity analysis and provide no other information about the system. Table 3 shows the differences in regulated peak flow magnitudes for various flood events.

Table 3. Regulated peak flows for various flood events for the Feather River below the confluence with the Yuba River

Percent chance exceedence (1)	**Regulated peak flow using the 1-day unregulated flow duration (cfs) (2)**	**Regulated peak flow using the 3-day unregulated flow duration (cfs) (3)**	**Regulated peak flow using the 7-day unregulated flow duration (cfs) (4)**
0.1	131,222	127,918	127,209
0.05	176,550	172,653	163,376
0.02	238,050	238,915	223,570
0.01	295,369	295,661	273,945
0.005	359,176	358,485	328,148
0.002	456,657	448,983	402,019

Figure 27 illustrates the variation of the peak flow transform curve for the Feather River above the confluence with the Yuba River. The critical duration is a 1-day unregulated flow for this location in the system. Using an unregulated flow duration different than the 1-day critical duration for this location will affect the peak regulated frequency curve, as shown in Figure 28. The peak regulated frequency curve developed using the 1-day unregulated flow duration accurately represents the system. Figure 28 shows that the peak regulated frequency curve becomes most sensitive to the critical duration for the smaller more frequent events and the larger less frequent events, specifically greater than the 10-year (p=0.1) event. A peak regulated frequency curve that accurately quantifies the larger less frequent events is important for flood protection, and is determined using only the critical duration. The other peak regulated frequency curves in Figure 28 are the results of a sensitivity analysis using the 3-day and 7-day unregulated flow durations and provide no other information about the system. The sensitivity of the peak regulated frequency curve due to the unregulated flow duration used will vary with site location. Table 4 shows the differences in regulated peak flow magnitudes for various flood events.

Table 4. Regulated peak flows for various flood events for the Feather River above the confluence with the Yuba River

Percent chance exceedence (1)	**Regulated peak flow using the 1-day unregulated flow duration (cfs) (2)**	**Regulated peak flow using the 3-day unregulated flow duration (cfs) (3)**	**Regulated peak flow using the 7-day unregulated flow duration (cfs) (4)**
0.1	79,623	82,342	78,770
0.05	107,627	109,596	99,119
0.02	159,554	162,226	138,238
0.01	205,643	210,264	183,100
0.005	255,078	261,145	230,052
0.002	328,429	334,055	296,186

The critical duration for inflows to a reservoir depends upon the reservoir's storage capacity, its outlet capacity, operating rules, and the uncontrolled area between the dam and downstream locations of interest. Therefore, the critical duration will vary for different locations within a system. Determining the correct critical duration to be used with the peak flow transform is a key step in developing a peak regulated frequency curve that accurately represents a specific location in the system. This sensitivity analysis shows that the peak regulated frequency curve for these two locations is most sensitive to the critical duration for flows higher than the 10-year (p=0.1) event. Using the incorrect unregulated flow duration to determine the peak regulated frequency curve will likely misrepresent the peak regulated flows for the higher less frequent events which are crucial to determining flood protection.

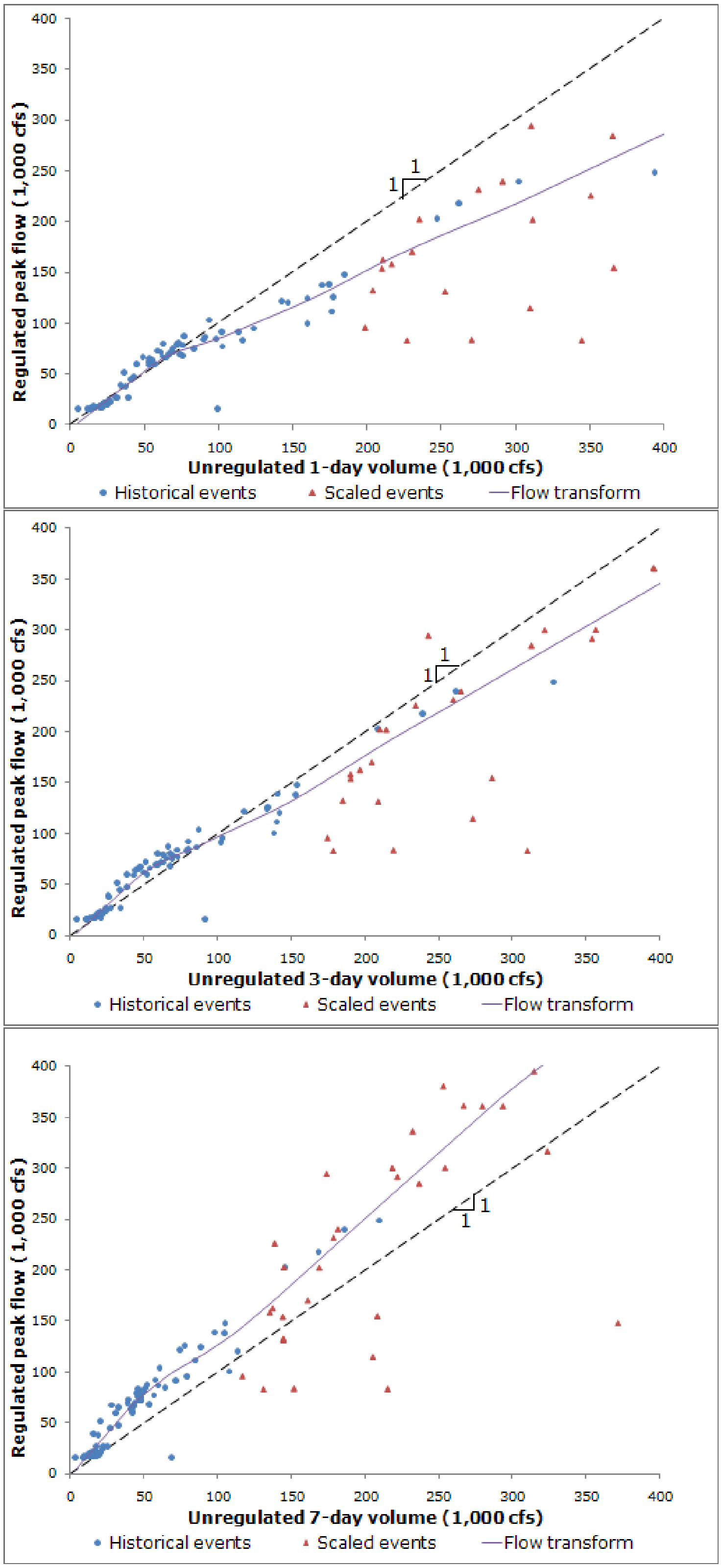

Figure 25. Illustration of unregulated-regulated flow transform curves at the Feather River below the confluence with the Yuba River for various unregulated flow durations; 3-day is the critical duration

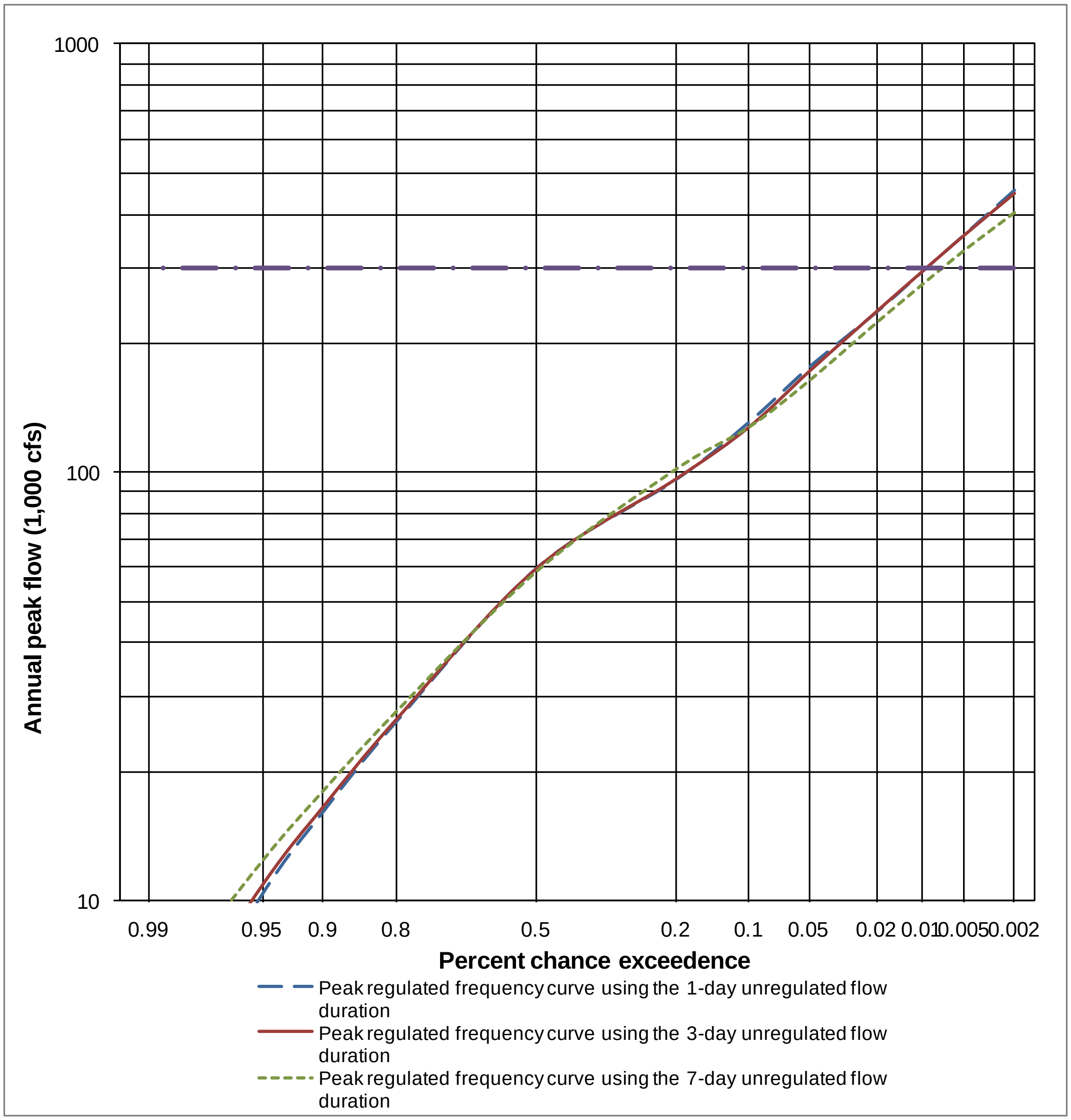

Figure 26. Illustration of peak regulated frequency curves at the Feather River below the confluence with the Yuba River for various unregulated flow durations; 3-day is the critical duration

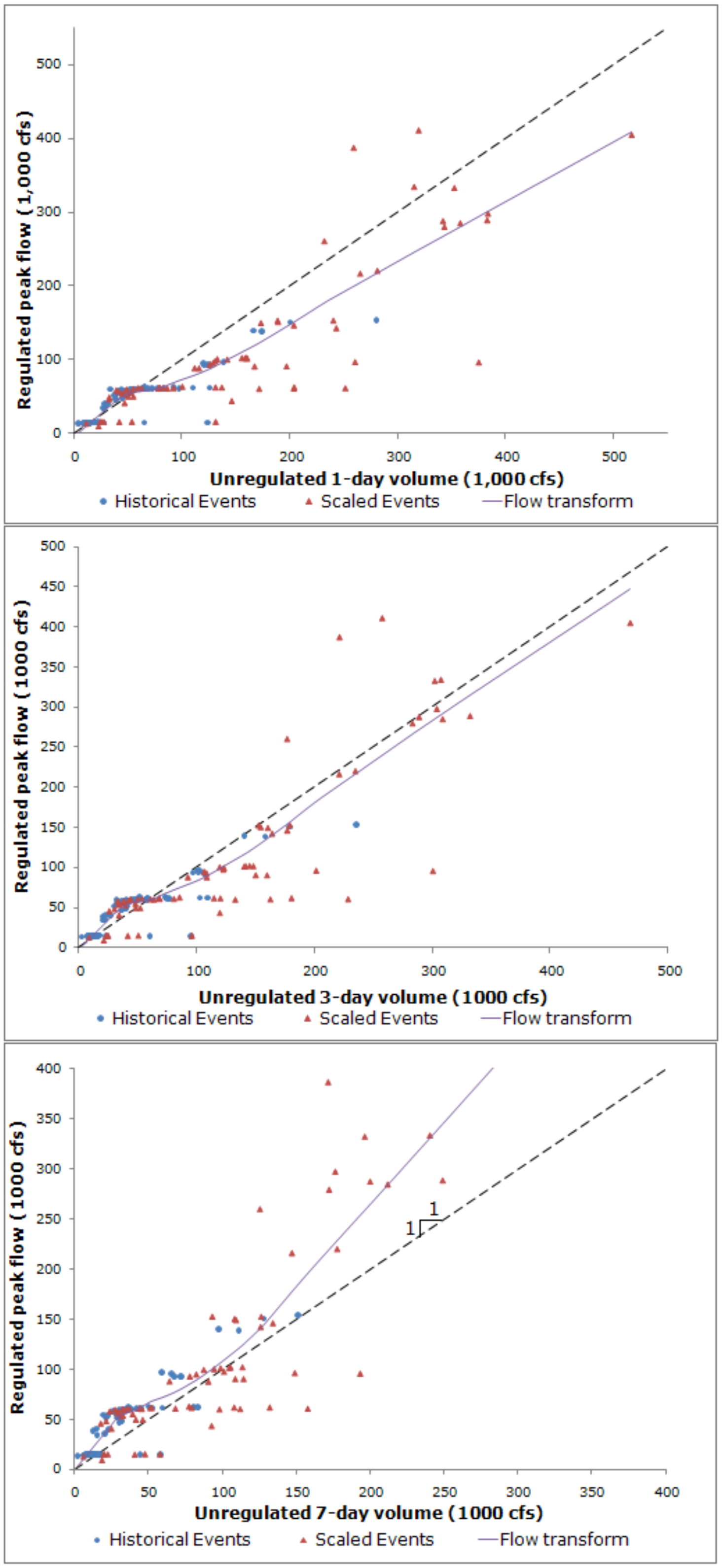

Figure 27. Illustration of unregulated-regulated flow transform curves at the Feather River above the confluence with the Yuba River for various unregulated flow durations; 1-day is the critical duration

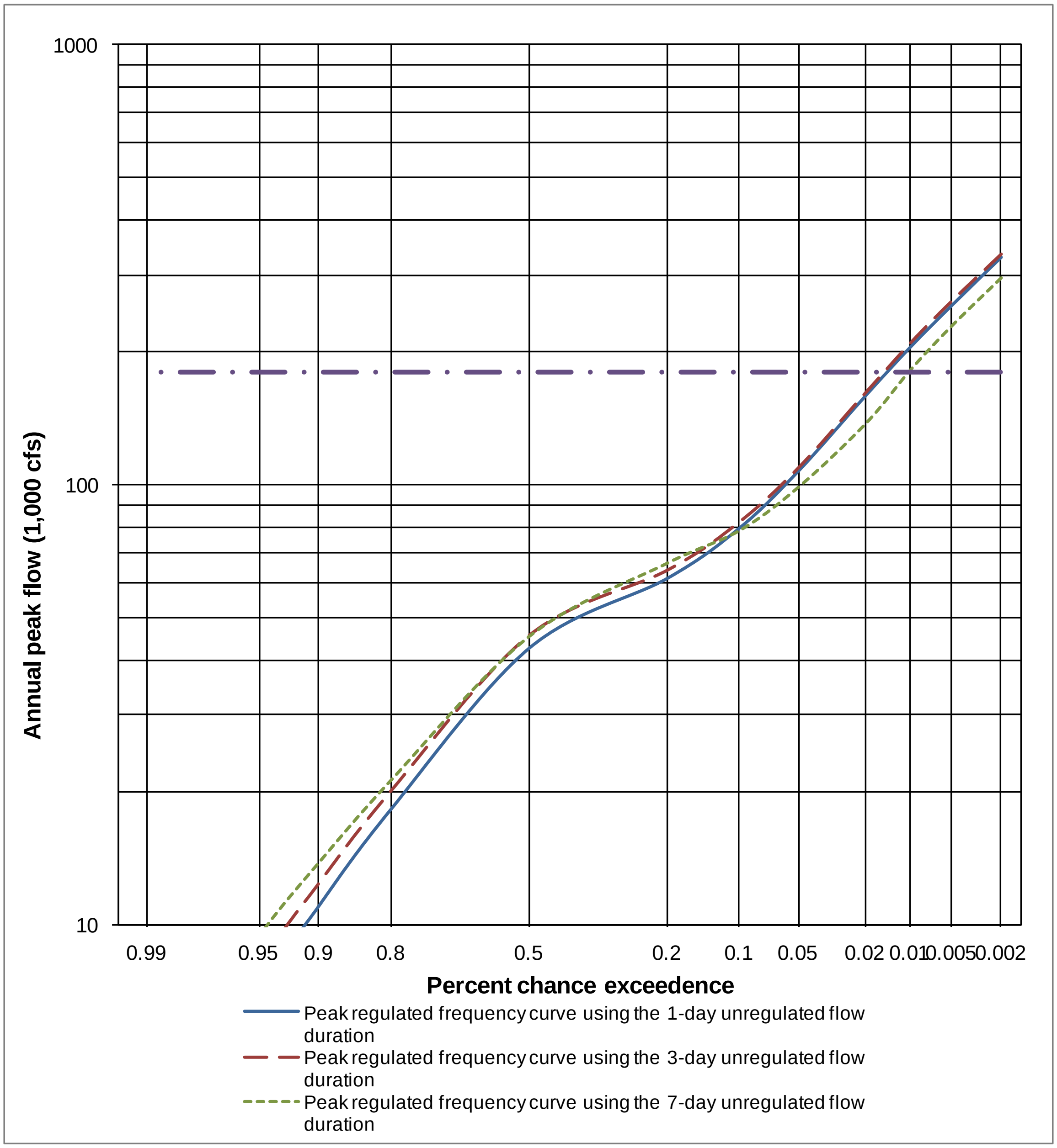

Figure 28. Illustration of peak regulated flow frequency curve at the Feather River above the confluence with the Yuba River for various unregulated flow durations; 1-day is the critical duration

Chapter 5.0 – Conclusions

While unregulated frequency curves can be developed using statistical models, such as those described in Bulletin 17B (IACWD 1982), the operated nature of regulated flows makes these methods insufficient to develop the regulated frequency curves. The shape of the regulated flood frequency curve varies with at-site storage characteristics of the reservoir, the frequency of inflow peak, volumes, and storm durations, and the reservoir’s operating policies. The regional information used to increase record lengths is only useful for determining the reservoir inflow frequency curve. The duration of flood volumes critical to determining peak annual outflow, operational contingencies, and the relationship between regulated and unregulated flow values must be considered when converting the inflow frequency curve to a regulated frequency curve (Goldman 2001).

A regulated frequency curve must be developed from the unregulated frequency curve and a corresponding peak flow transform. A peak flow transform translates an unregulated flow of a given quantile to the corresponding regulated flow for that same quantile. The final regulated flow frequency curve is sensitive to the shape of this curve.

This paper examined peak flow transforms developed using two reservoir operating rules: 1) optimal peak reduction with perfect foreknowledge of the flood hydrograph; and 2) minimized exceedences of downstream channel capacity. Four simplified inflow hydrograph shapes were chosen to represent a variety of floods. While perfect foreknowledge of the flood hydrograph is rare in real-time operations, the transforms developed using the Maximum Peak Reduction Rule are the ideal, best-case examples. The transforms developed using the Downstream Channel Capacity Rule are more realistic for real-time operations because the reservoir operates solely on its operating rules and the current inflows. The flow transforms developed using these two operating rules seem likely to bound the range of peak flow transforms.

The Feather River – Yuba River Confluence case studies examined the development of the regulated frequency curve for more complex systems. In these examples, the flow transform curves represented the available storage in the reservoir, offstream storage due to capacity exceedence or levee failure, reservoir operation, and historical storm patterns and timing. Determining the critical duration for the location of interest to be used with the peak flow transform is essential in developing a peak regulated frequency curve. Using an incorrect unregulated flow duration could misrepresent the peak regulated flows on the frequency curve, specifically for the larger less frequent events.

Flows determined using HEC-ResSim are estimates of what would occur during a range of flood events. Real-time emergency flood operations vary from the operating rules because of unforeseen aspects of individual events. Corps guidance states that “in constructing frequency curves of regulated flows, actual operation is rarely perfect and that releases will frequently be curtailed or diminished because of unforeseen operation contingencies. Also, where flood forecasts are involved in reservoir operation, these are subject to considerable uncertainty and some allowance will be made for uncertainty during operation. In accounting for these factors, actual control of floods is somewhat less than could be expected if full release capacities and downstream channel capacities where utilized efficiently and if all forecasts were exact” (USACE 1993). Regulated frequency curves, developed from peak flow transforms, do not represent actual reservoir operation but are simplifications for flood management planning.

Explanation of Variables

d – Duration of peak

$Q_{p,in}$ – Peak inflow

$Q_{p,out}$ – Peak outflow

Q_c – Downstream channel capacity

Δq_p – Difference of peak inflow and peak outflow

r – Rate of rising or recession limb

S_t – Storage in flood control pool at time t

S_{max} – Maximum storage in flood control pool

t – time

V – Reservoir flood control storage volume

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